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LOCAL SUBSIDENCE OF THE GOOSE CREEK OIL FIELD

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ABSTRACT

In 1918, Gaillard peninsula, the center of the Goose Creek Oil Field, on Galveston Bay, began to subside. The geology of the field and the nature of the subsidence are discussed. It is concluded that subsidence was caused by the extraction of oil, water, gas, and sand from beneath the surface.

The low flat coastal plain of Texas, following a geologically recent uplift of the coast, was bordered on its seaward side by a more or less continuous offshore bar separating a shallow lagoon from the open waters of the Gulf of Mexico. The fairly typical "shoreline of emergence" thus produced was later modified by a slight submergence which partly drowned the lower ends of valleys draining into the Gulf, so that today the inner margin of the lagoon frequently makes broad indentations into the land. Galveston Bay (Fig. 1) is such an indentation, and one of its subdivisions on the northwest is known as San Jacinto Bay. Into the latter body of water drains a little stream known as Goose Creek.

THE PHENOMENA OF SUBSIDENCE

In 1917 a prolific oil field was developed near the mouth of Goose Creek, and during 1918 and subsequent years, millions of barrels of

oil were removed from beneath its surface. Beginning in 1918 it became apparent that Gaillard Peninsula, near the center of the field (Fig. 2), and other nearby low land was becoming submerged. Elevated plank roadways or walks were built from the mainland to the derricks (Fig. 4). Derrick floors had to be raised. Vegetation was flooded and killed, and finally all of the peninsula disappeared

FIG. 1.—Location map

beneath the water (Fig. 3). The change appeared to be gradual but did not go unnoticed. The maximum measured subsidence is now more than 3 feet and the area affected is $2\frac{1}{2}$ miles long by $1\frac{1}{2}$ miles wide, the longer axis running approximately east-west. Outside this area no change in elevation can be detected, although repeated careful levels have been taken at intervals, both within the submerged area and outside of it.

In the little town of Pelley on the northern edge of the oil field (Fig. 7), cracks appeared in the ground running beneath houses,

across streets, and through lawns and gardens (Fig. 5). These cracks persisted, and recurrent movement along them resulted in dropping

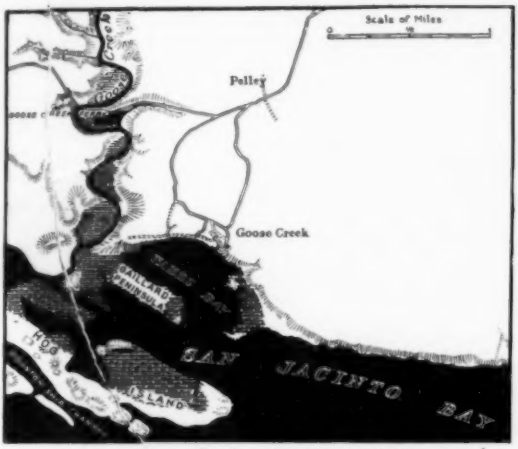

FIG. 2.—Goose Creek region before subsidence

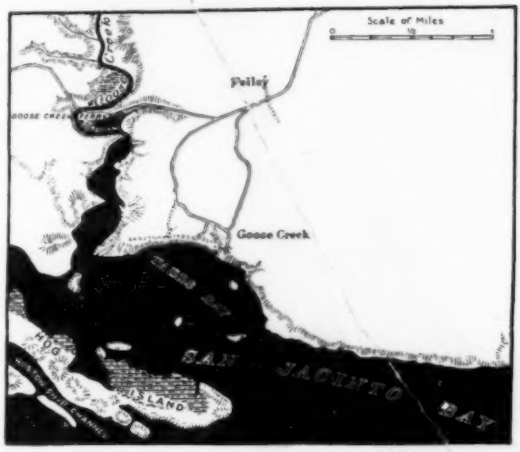

FIG. 3.—Goose Creek region after subsidence

the surface of the ground on the side of the cracks toward the oil field. The changes in elevation resulting from these movements

FIG. 4.—Looking east-southeast across Tabbs Bay, from a point east of Goose Creek. Gaillard Peninsula is to the right of this view.

FIG. 5.—Looking westward along fault fissure in town of Pelley, ½ mile north of Goose Creek. The land to the left (south) has dropped 16 inches at this point.

amounted to 16 inches or more in places. The movements were accompanied by slight earthquakes which shook the houses, displaced dishes, spilled water, and disturbed the inhabitants generally. Similar faults developed along the southern margin of the oil field on Hogg Island, the displacement here being again downward on the side toward the area of oil extraction, and varying from 3 to 12 inches in vertical extent (Fig. 6).

FIG. 6.—Looking eastward along one of several fractures on Hogg Island. At the left (north) the subsidence of the surface has caused the vegetation to be submerged and killed by salt water. Displacement along the Hogg Island fractures varies from 3 to 12 inches.

PRACTICAL ASPECTS OF THE PROBLEM

Submerged land in Texas belongs to the state and only the state can grant oil and gas leases on submerged lands. Consequently, when Gaillard Peninsula became submerged, the state claimed title to it and sought not only to dispossess the fee owner and the oil and gas lessee, but also to recover from them the value of the oil and gas removed from the premises subsequent to the time when the land became submerged. The question was taken into court and finally decision was rendered in favor of the defendants, that is, the claim

of the state of Texas was denied, and the present owners continue in possession. The basis for the decision was the court's acceptance of the contention that the subsidence at Goose Creek (which the defendants admitted) was not the result of natural processes but was caused by an act of man, namely, the removal of large volumes

FIG. 7.—Contours of equal subsidence (in feet) for eight-year period shown in light solid lines; for one-year periods, in heavy broken lines. Dots represent wells.

of oil, gas, water, and sand from beneath the surface. No act of man can operate to deprive another man of his property under the law. If the subsidence at Goose Creek had been a natural process, "an act of God," then presumably title to the submerged land would have passed to the state, and property worth millions of dollars would have been lost to the owner of the land and to the operating companies.

Inasmuch as subsidence of the earth's surface due to the exploitation of an oil field appears to be an extremely rare occurrence, if indeed the Goose Creek case be not unique in geological literature;

and further, inasmuch as the Goose Creek case affords an excellent illustration of the solution of an important legal controversy by the use of geologic and physiographic data, it is thought worth while to present the facts somewhat fully. The senior author's acquaintance with the region was gained in his capacity as chief geologist of the Humble Oil and Refining Company, lessee of Gaillard Peninsula. The junior author was retained as consulting physiographer in connection with the court proceedings mentioned above, and studied the phenomena of subsidence in the Goose Creek region.

GEOLOGY OF THE GOOSE CREEK OIL FIELD

Goose Creek is situated in a region of geologically young rocks. The Eocene is buried to a depth of at least 5,500 feet. The beds above the Eocene are loose sands and clays only slightly more compacted than sea-bottom muds.

The section penetrated by wells at Goose Creek from the surface downward includes the following succession of formations:

TABLE I

Period	Formation	Character	Approximate Thickness (Feet)
Recent and Pleistocene	Beaumont Clay	Clays of fresh or brackish water deposition. Subordinate sand lenses	300 to 400
Pleistocene and Pliocene	Lissie Sands	Sands with subordinate clays and a little gravel of fresh or brackish water deposition	400
Pliocene and Miocene	Fleming Clays	Clays with sand lenses. Brackish water and marine deposition	3,000 to 4,000
Oligocene	Corrigan or Catahoula Sands	Marine sands and clays	1,000+

These beds are all essentially unconsolidated. The clays or gumbos carry as much as 30 per cent (by weight) of moisture, whereas ordinary clays or shales of Cretaceous age in the Gulf region carry only 10 per cent. The sands are generally soft so that they flow into the wells, although, locally and in part, they may be cemented by calcium carbonate. Limestone occurs only as small concretions in the Beaumont and Fleming clays. All the sands are lenticular in extent and nowhere, except possibly in the Lissie, is there a free intercommunication of fluids over the whole area.

Oil is encountered sparingly in the Lissie at a depth of 500 feet, and in quantity in sand lenses throughout the Fleming clays, and again in the upper part of the Oligocene. Commercially important production comes from depths of 1,000 feet, 1,500 feet, 1,700 feet, 2,000 feet, 2,400 feet, 2,600 feet, 2,800 feet, 3,000 feet, 3,300 feet, 3,700 feet, and 4,100 feet.

The geologic structure, as displayed in the Miocene and younger beds, is a low dome, while the Oligocene, beneath an unconformity, appears to be profoundly and intricately faulted. Goose Creek is not a salt-dome field of the ordinary type. No salt has ever been encountered in drilling, although centrally located wells have gone to depths greater than 5,000 feet. In the salt-dome fields of the Gulf Coast region salt is encountered at depths of from 300 to 2,000 feet.

NATURE OF THE SUBSIDENCE

Numerous benchmarks were established throughout the Goose Creek region some years ago, and these have been resurveyed and new benchmarks established at intervals since the original survey. We thus have precise figures showing amounts of subsidence at something like eighty points in the affected area and its immediate vicinity. Not all of these record the total subsidence, since many of the benchmarks were established after the sinking of the surface became evident. Sufficient accurate data are available to make it possible to draw contours through points showing equal amounts of subsidence during the 8-year period 1917 to 1925 inclusive, and again for the 1-year period 1924 to 1925.

For the 8-year period the records are less numerous than could be desired; consequently the contours of equal subsidence are necessarily more generalized and appear more regular than would be the case if more data were available (Fig. 7). There can be no doubt, however, that the contours show correctly the essential fact that a local "dishing" of the earth's surface has occurred in the Goose Creek region, the central area of greatest subsidence corresponding approximately with the center of the oil field. Unfortunately we do not possess sufficient data to demonstrate that the contours for the whole 8-year period continue to decrease outward to a *zero contour* or line of proved absence of any subsidence,

although the figures available indicate that this is probably the case. Contours for the 1-year period for which we have ample data do prove conclusively that the continuing subsidence is purely a local phenomenon; for they show a central area of maximum subsidence, an intermediate area of less subsidence, and an outer area of absolute stability. The more abundant data for the 1-year period permit us to draw these contours with greater accuracy, with the result that they appear less regular than those for the 8-year period.

ALTERNATIVE THEORIES

The disturbance certainly has no connection with the supposed gradual subsidence of the Atlantic and Gulf coasts which many geologists and laymen believe to be in progress. The junior author has shown in a number of published works that in so far as the Atlantic coast is concerned, the belief in a continuing general subsidence is based on a misinterpretation of the evidence, and on a failure to recognize certain indications that the known post-glacial subsidence ceased several thousand years ago, since which time the land and sea have remained remarkably stable. In his opinion the situation with respect to the Gulf coast is the same. But even if a general subsidence of the Gulf coast be now in progress, the disturbance at Goose Creek cannot be related to it. General changes of level affect large areas rather uniformly, and, so far as known, never show such sharp differences of rate of sinking within short distances as characterize the Goose Creek region. The greatest rate of subsidence admitted by most geologists for the east coast of North America is 1 or 2 feet per century, whereas the sinking at Goose Creek has amounted to more than 3 feet in 8 years. The surveys demonstrate that the disturbance at Goose Creek rapidly dies out to nothing in all directions from the center. These facts show how impossible it should be to confuse the sinking at Goose Creek with the phenomena of general coastal subsidence.

The Goose Creek disturbance is equally unrelated to the changes of mean sea-level observed at Galveston by the United States Coast and Geodetic Survey. The extent of these changes is shown in Table II furnished by Survey officials.

It has recently been shown by H. A. Marmer[1] that mean sea-level may vary from year to year by an amount which sometimes exceeds a foot. These changes are due largely to meteorological and astronomical causes, and occur in cycles of several years' duration. The junior author has shown that mean sea-level may also change with changes in the form of the shore line, natural or artificial changes in the size of inlets, deepening of channels into bays, and other alterations of a local character. Careful study of the conditions

TABLE II

MEAN SEA-LEVEL AT GALVESTON

Year	Height (feet)	Year	Height (feet)
1904	3.35	1914	3.57
1905	3.38	1915	3.45
1906	3.39	1916	3.50
1907	3.44	1917	3.25
1908	3.37	1918	3.33
1909	3.48	1919	3.70
1910	3.22	1920	3.59
1911	3.35	1921	3.92
1912	3.51	1922	3.72
1913	3.63	1923	3.78

at Galveston would probably indicate that the changes reported there are of a temporary nature and possibly due in part to artificial changes in the channel into the harbor. Or it may be found that the apparent slight average rise in the sea-level here is in part due to the inaccuracy in references to the fixed zero which are not wholly satisfactory because of unusual difficulties experienced in connection with the operation of this station.[2] In any case, the reported change in sea-level at Galveston is so small as compared with the changes at Goose Creek as to make clear the fact that they are not related. Furthermore, it should be noted that since all measurements in the Goose Creek area are referred to fixed benchmarks on the land, and not to tide gauges recording mean sea-level, the changes at Goose

[1] "Sea Level along the Atlantic Coast of the United States and Its Fluctuations," *Geographical Review*, XV (1925), 438–48. Also, "Mean Sea Level and Its Variations," *Association of American Geographers, Annals*, XV (1925), 106–18.

[2] Personal communication from Acting Director of the U. S. Coast and Geodetic Survey.

Creek are not only independent of, but are in addition to, any supposed changes indicated by the Galveston records. The Goose Creek sinking certainly has nothing to do with any real or apparent changes in the average level of the sea.

Erosion of clay coasts by waves or currents frequently produces local subsidence, with cracking and displacement of the surface far back from the actual shore. The Goose Creek disturbance clearly has no relation to such a process. The shore cliffs do not have the appearance characteristic of cliffs receding under active wave attack. Before the subsidence a large proportion of the affected area had its shores effectively protected from vigorous wave and current action by marshy forelands in front of them. The fact that the subsidence is distributed indifferently over both land and water areas, and that low marsh land on Gaillard Peninsula has suffered equally with the higher clay uplands, is against the wave- or current-sapping theory. The sheltered position of the affected area—in Tabbs Bay and adjoining waters forming a sheltered branch of San Jacinto Bay, which in turn is a fairly sheltered arm of the nearly closed Galveston Bay—is strongly against the wave-sapping theory; and strong currents at the point of maximum subsidence in Tabbs Bay appear to be practically impossible. If any subsidence were to occur in this region due to wave or current action, it should be along the more exposed neighboring shores where conditions are in all respects more favorable; but no such changes of level are known in these areas.

The Goose Creek depression cannot reasonably be interpreted as a sink hole formed by the solution of limestone, salt, or other soluble formation in depth, under natural conditions. Neither limestone nor salt is encountered by the drill. If the Goose Creek oil field is developed over a salt dome, the salt occurs at depths greater than 5,000 feet. In any case, the solution theory can be applied, if at all, only by recognizing that artificial exploitation of the oil field brought about conditions favorable to rapid solution, as by creating a vigorous circulation of water which did not previously exist. This is clear from the fact that subsidence corresponds so exactly, both in time of occurrence and in area affected, with the time and extent of the oil extraction. The force of this argument can better be appreciated after reading the paragraphs which follow.

CAUSE OF THE SUBSIDENCE

In our opinion the cause of the subsidence is to be found in the extensive extraction of oil, water, gas, and sand from beneath the affected area. The purely local character of the disturbance, the facts that the area of subsidence coincides with the area of extraction, that the period of sinking coincides with the period of extraction, and that continued extraction is accompanied by continuing subsidence as shown by the latest measurements, all point unmistakably to this conclusion. These points will be considered in order.

The subsidence is purely local, and its area corresponds closely with the area of extraction. This will be apparent from an examination of Figure 7, in which both the area and the amount of subsidence are shown by contours, and the area of extraction by the distribution of wells. It is noticeable that the wells cover an area that is rudely oval, with the longer axis east-west; and the contours of equal subsidence exhibit the same pattern. The center of maximum subsidence is near the center of the drilled area; but the 8-year contours are more closely spaced on the north than on the south, indicating a steeper slope where the wells are most closely grouped, as if slumping were most effective where the greatest amount of material was taken out. The 1-year contours, based on more abundant data, bring out a truly remarkable correlation between the area of subsidence and the area of extraction. At the points marked *A*, *CD*, and *F* are extensions or protuberances of the drilled area where groups of wells reach out beyond the average perimeter of the field, while between, at *B* and *E*, are relatively barren areas with fewer wells. The contour showing a subsidence of .10 foot in 1 year, while not tracing exactly the line between few and abundant wells, corresponds so closely with areas of greater extraction, bending outward where the drilling was carried outward, that it is difficult to escape the conclusion that it shows a distinct extension of the subsidence into areas of extended drilling.[1] The location of the earth fractures near the margins of the field, one on the north and one on the south, with

[1] In the southern part of the field, where water areas predominate and data for locating the contours are less abundant, the coincidence is less marked.

the down-drop in each case toward the center of extraction, is highly significant. Surely the coincidence of the area of subsidence with the area of extraction is remarkably close, and implies a causal relationship.

The time of the subsidence corresponds with the time of extraction. Prior to the development of the oil field in 1917 no indications of subsidence appear to have been noted in this area. The low land of Gaillard Peninsula has served as grazing-ground for cattle for nearly a century, and changes in its size or form or elevation would readily be observed; yet none are reported. Maps made before 1850 show the same shore lines as existed in 1917. Then came the opening of the oil field, and a year later the subsidence became evident. In 8 years the change of level amounted to 3 feet, the shore lines were completely altered, much land submerged, and great areas of vegetation killed by salt water. A closer coincidence between time of subsidence and time of extraction could not be imagined.

Continued extraction is accompanied by continuing subsidence. This is made apparent by recent surveys, the change for the year 1924–25 being indicated by the broken-line contours on Figure 7. For this year the maximum subsidence was .25 foot near the center of the field, the amount decreasing outward in all directions until areas of absolute stability were found about the margins of the affected district.

It is safe to say that the aggregate volume of oil, gas (at 1,000 lbs. per square inch pressure), water, and sand removed from Goose Creek since 1917 will exceed 100,000,000 barrels, or about 500,000,000 cubic feet. When this volume is compared with the calculated space between the former surface and the present surface over the Goose Creek oil field, it is found that there is a considerable excess of "volume of removal" over the "volume of subsidence." As a matter of fact, the estimated volume of materials removed from beneath the surface at Goose Creek is nearly five times as large as the calculated volume between the planes representing the present surface and the former surface of the land. In other words, subsidence, to date, has accounted for only about 20 per cent of the total subterranean voids created by the removal of oil, gas, water, and sand.

CONCLUSION

The facts presented above seem to justify the conclusion that the Goose Creek subsidence was directly caused by the extraction of oil, water, gas, and sand from beneath the surface, beginning in the year 1917. In this connection it should be noted that the coastal plain beds at this locality consist largely of unconsolidated clays or gumbos, and that the oil sands occur in discontinuous lenses. Under such circumstances the removal of oil and water from the sands is not followed by a free flow of water into the pore spaces from distant localities, because the compact nature of the clays, which completely surround and isolate the sand lenses, prevent such ready flow of water. The pore spaces are therefore occupied by water draining in more slowly from the adjacent clays; and it is a well-known fact that the draining of clays causes them to become more compact. This, in turn, would permit subsidence of the overlying surface.

Other important factors, undoubtedly, are the reduction of pressure in the sand reservoirs from values of 1,000 or 1,200 pounds per square inch to atmospheric pressure, and the actual removal of sand itself from the reservoirs. In the reduction of moisture content, escaping gas has been a material factor. These factors have combined to produce a draining and a drying of the clays, with consequent shrinkage; and in the absence of competent beds to support the overlying deposits, the results have become apparent in a remarkable dishing of the surface of the Goose Creek field.

THE POTASH-SODA FELDSPARS

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ABSTRACT

Both potash- and soda-feldspar end-members are believed to be trimorphous. The Millard–Michel Lévy theory of submicroscopic twinning and the theory of polymorphism are considered to be independent. The former is not competent to explain the results of thermal analysis or the cusps in the thermal expansion curves. The consequences of trimorphism, including perthites of two generations, are discussed.

INTRODUCTION

Recent advances in the study of the feldspars, especially by Winchell, Kôzu, Endô, Saiki, and Mountain, furnish the basis for a discussion of the possible trimorphism of each of the end-members of the potash-soda series. Winchell's emphasis is upon the relationship of the optical properties and composition on the basis of trimorphism. My purpose is to suggest, more particularly by means of diagrams, the process of crystallization of these feldspars. Identification of feldspars microscopically is essential to a proper study of rocks; but in order to appreciate rocks and minerals genetically, the crystallization phenomena must be studied—hence the desirability of investigating the potash-soda feldspars.

First, however, it is well to recognize that most minerals consist of more than one end-member. The too common practice of assigning a single chemical formula to a mineral that consists of solid solutions is more of a hindrance than a help. There appears to be more emphasis placed upon the search for new minerals than there is upon making any serious effort to put the common rock-making minerals upon a true scientific basis.

MINALS VERSUS MINERALS

Too many mineralogists employ the names of minerals in two senses:[1] First, as the name of an end-member of a system; second,

[1] H. L. Alling, *Jour. Geol.*, Vol. XXIX (1921), p. 218.

as a compositional range within that system. To illustrate: (1) "Microcline" used as a "minal," pure $KAlSi_3O_8$,[1] as one of the components of perthite; (2) "microcline" as a "mineral," as found in nature. This is never pure potash feldspar, but always contains $NaAlSi_3O_8$—sometimes as high as 50 per cent!—and smaller amounts of $CaAl_2Si_2O_8$.[2] To assign a single formula to "microcline" as a mineral, found in nature, is a failure to state the truth. A typical example would be: $Mic_{85}Ab_{10}An_5$.

If the metallographer followed this bad example, he would assign a single chemical formula to cast iron and ignore the carbon content![3] To the metallographer, "metals" are components, while solid solutions and definite chemical compounds are "meterals."[4] Hence I proposed "minal"[5] to mean the end-members of a mineralogical system to which a single formula can be given.

Minerals, therefore, are composed of minals. How absurd it would be if the composition of an andesine, $Ab_2An_1(Ab_{66.7}An_{33.3})$ should be written $Na_2CaAl_4Si_4O_{24}$!

"Minal" may be provisionally defined as a natural inorganic solid usually capable of assuming definite geometrical forms, of definite chemical composition, possessing definite physical properties that enter into the composition of natural minerals as actually found. Minals, with a few exceptions,[6] are not found by themselves. To minals a single chemical formula can be assigned.

A "mineral" may be defined for our purpose as a natural inorganic solid usually capable of assuming definite geometrical forms, of characteristic chemical composition and characteristic physical properties, composed of one or more minals. When two or more minals are present they exist as either interminallic compounds or

[1] In this paper denoted as a $KAlSi_3O_8$.

[2] Traces of $BaAl_2Si_2O_8$, $SrAl_2Si_2O_8$, $LiAlSi_2O_6$, $Na_2Al_2Si_2O_8$, etc., are often present to modify the optical properties, frequently a good deal.

[3] As cementite and graphitic carbon.

[4] H. M. Howe, *Metallography of Steel and Cast Iron*, p. 232; Albert Saveur, *Metallography and Heat Treatment of Iron and Steel*, pp. 293–94.

[5] Alling, *op. cit.*

[6] A few appear to occur: optical quartz, calcite, fluorite, etc.

solid solutions or mixtures of solid solutions, in which case no *single* formula should be assigned. That is to say, most minerals as found in nature are polycomponent systems.[1]

Within mineral systems occur many series that consist of solid solutions. For these the variations of the optical properties and the change in chemical composition are direct functions of each other as they are in the plagioclase feldspars. The relation of optical properties to chemical composition in a system of mineral intergrowths is much more complicated. Our information concerning these relationships in the case of the perthitic feldspars is still far from complete. This condition may be due to the trimorphism of the end-members or minals, as Winchell[2] suggests, as well as to secondary changes taking place following primary deposition.

POLYMORPHISM

POTASH FELDSPAR

Potash feldspar, $KAiSi_3O_8$, exists in two and possibly three crystal modifications. $KAlSi_3O_8$, crystallizing at high temperatures, is monoclinic[3] and possesses optical characteristics different and distinct from orthoclase formed at a lower temperature. This high temperature form is sanidine. Orthoclase appears, on the basis of our present knowledge, to be stable at intermediate temperatures. Winchell calls this modification "adularia,"[4] which I think is unfortunate in that some adularias are hydrothermal in origin.

Many mineralogists regard orthoclase and microcline as iden-

[1] Garnets.—W. E. Ford, *Amer. Jour. Sci.* (4), Vol. XL (1915), pp. 33–49.
Pyroxenes.—A. N. Winchell, *ibid.* (5), Vol. VI (1923), pp. 504–20.
Amphiboles.—Winchell, *ibid.* (5), Vol. VII (1925), pp. 287–310; *Amer. Min.*, Vol. X (1925), pp. 335–41.
Micas.—Winchell, *Amer. Jour. Sci.* (5), Vol. IX (1924), pp. 309–27, 415–30.
Scapolites.—Winchell, *Amer. Min.*, Vol. IX (1924), pp. 108–12.
Zeolites.—Winchell, *ibid.*, Vol. X (1925), pp. 88–97, 152–57, 166–74.
Melilites.—Winchell, *Amer. Jour. Sci.* (5), Vol. VIII (1924), pp. 375–84.

[2] A. N. Winchell, "Studies in the Feldspar Group," *Jour. Geol.*, Vol. XXXIII (1925), pp. 714–27.

[3] Des Cloizeaux, *Comp. Rendu*, Vol. LXXXII (1876), pp. 1017–22; *Bull. Soc. Fr. Min.*, Vol. VI (1883), pp. 89–121.

[4] Winchell, *Jour. Geol.*, Vol. XXXIII (1925), p. 719.

tical, differing only in the degree of twinning.[1] Others,[2] through studies of specific gravities, indices of refraction, thermal properties, including thermal expansion, believe that these compounds are polymorphous.

Although Michel Lévy[3] has shown that the extinction angle on the (001) face of adularia would be the consequence of submicroscopic twinning of microcline units, it is my belief that the theory of polymorphism is not thereby disproved. Neither theory excludes the other; each one can be independent. That is to say, sub-microscopic twinning may be competent to explain the extinction angle, but fails to account for other optical properties and cusps in the thermal expansion curves.

Hadding's[4] results, which Vogt[5] accepts as disproof of polymorphism, are stated by Wyckoff[6] to have been "reported in such meager detail that its data are of limited usefulness."

Kôzu and Endô[7] state that the Laue röntgenograph of adularia[8] from St. Gothard showed ". . . . no special change . . . . at two different temperatures, 25° C. and 1060° C. from which we may conclude that the crystal structure of adularia is stable for almost the whole range of temperature in the crystalline state." Yet the optical studies of Des Cloizeaux and the thermal work of Merwin show a slow inversion at 900° C. This change is very sluggish. I question

[1] E. Mallard, *Ann. des mines*, Vol. X (1876), p. 10; A. Michel Lévy, *Bull. Soc. Fr. Min.*, Vol. II (1879), p. 135; Rosenbusch-Iddings, *Microscopic Phys. Rock-forming Min.*, p. 320; W. C. Brögger, *Die Mineralien der sudnorwegish Granitpegmatigange*, 1906; Hadding, *Lund's Universitets Aarskrift*, Vol. XVII (1921); J. H. L. Vogt, *Jour. Geol.*, Vol. XXXI (1923), p. 411 n.

[2] J. H. L. Vogt, as cited by C. H. Warren, *Proc. Amer. Acad. Arts and Sci.*, Vol. LI, No. 3 (1915), p. 144; Ph. Barbier, *Bull. Soc. franç. Min.*, Vol. XXXI (1908), pp. 152–67; H. L. Alling, *Jour. Geol.*, Vol. XXVIII (1921), p. 207; *Jour. Geol.*, Vol. XXXI (1923), pp. 291, 293; Merwin, *Jour. Wash. Acad. Sci.*, Vol. I (1911), p. 59; Kôzu and Endô, *Sci. Rpts. Tohoku Imp. Univ.* (Ser. 3), Vol. I, No. 1, p. 16.

[3] *Bull. Soc. Fr. Min.*, Vol. II (1897), p. 135.

[4] Assar Hadding, "Rontgengraphische Untersuchung von Feldspat," *Lunds Univ. Aarskr.*, Vol. XVII (1921), pp. 3–25.

[5] J. H. L. Vogt, *Jour. Geol.*, Vol. XXXI (1923), p. 411 n.

[6] R. W. G. Wyckoff, *The Structure of Crystals* (*Chem. Cat. Co.*, 1924), p. 413.

[7] Kôzu and Endô, *Sci. Rept. Tohoku Imp. Univ.* (Ser. 3), Vol. I, No. 1, p. 16.

[8] K-feld $_{88.3}$ Na-feld$_{9.3}$ Ca-feld$_{2.4}$.

whether these Japanese investigators heated their specimens slowly enough and maintained them at high temperatures for a long enough time to obtain inversion.

Hence, proof of the polymorphism of these minals depends upon any discontinuous change in any physical property on change in temperature. I believe that in specific gravities, indices of refraction, thermal expansion and thermal analysis we have sufficient evidence to assume the trimorphism of both $KAlSi_3O_8$ and $NaAlSi_3O_8$.

The potash-feldspar minals are given in Table I.

TABLE I

POTASH-FELDSPAR MINALS

	Formula	Name	Temperature
Monoclinic.....	γ $KAlSi_3O_8$	Sanidine	High
Monoclinic.....	β $KAlSi_3O_8$	Orthoclase	Intermediate
Triclinic.....	α $KAlSi_3O_8$	Microcline	Low

SODA FELDSPAR

Merwin[1] found that albite inverts at about 900° C. to a high-temperature form, barbierite,[2] which is monoclinic. $NaAlSi_3O_8$ with about 10 per cent of $KAlSi_3O_8$ crystallized in a pseudomonoclinic modification which has been called "anorthoclase." I have differed with previous writers in the use of the name,[3] using it not for a stable soda-rich mineral of the alkali series, but for a metastable solid solution of two minals. If there is a third form of $NaAlSi_3O_8$, I should be inclined to follow Winchell and call it analbite.[4]

Hence the soda minals are as given in Table II.

STABLE RELATIONS

The experimental difficulties in establishing the range of stability of each of these six minals are so formidable that criticism of the above should be tempered. Our present knowledge seems to be:

[1] *Jour. Wash. Acad. Sci.*, Vol. I (1911), p. 59.

[2] Schaller, *Bull. Soc. Fr. Min.*, Vol. XXXIII (1910), p. 320; *Zeit. Kryst.*, Vol. I (1911), p. 347; *Jour. Wash. Acad. Sci.*, Vol. I (1911), p. 114; *U.S. Geol. Surv. Bull.* 509 (1912), p. 40. See also, *Bull. Soc. Chim. Fr.*, Vol. III (1908), p. 894; *Bull. Soc. Fr. Min.*, Vol. XXXIII (1910), p. 81.

[3] Alling, *Jour. Geol.*, Vol. XXIX (1921), p. 235.

[4] See Dana, "Abnormal Albite," *System of Min.*, 1892, p. 330.

1. That above 950°–900° C. sanidine is stable;

2. That between 650°–700° C. and 900° C. orthoclase is stable;

3. That below 650° C. microcline is stable, although Merwin states that "microcline" appears to be stable to its melting-point;[1]

4. That above 900° C. barbierite is stable;

5. That perhaps between 900° C. and an unknown lower temperature albite is stable;

6. At low temperature analbite is stable, especially if a little potash feldspar (modification as yet unknown) is present in solid solution.

TABLE II

SODA-FELDSPAR MINALS

	Formula	Name	Temperature
Monoclinic	γ $NaAlSi_3O_8$	Barbierite	High
Triclinic	β $NaAlSi_3O_8$	Albite	Intermediate
Triclinic	α $NaAlSi_3O_8$	Analbite	Low

Yet these minals do not invert with equal ease and speed at the indicated inversion temperatures. That is, the stability is not solely dependent upon temperature.

Unquestionably the application of pressure[2] and shearing-stresses accelerate inversion[3] in some cases, but much further work is needed here.

The rate of cooling is very important in effecting stability relations. Frequently inversion fails to occur except when the specimen is cooled *very* slowly. The failure to invert introduces additional complications. The presence of a high-temperature form in a rock as collected should, when our knowledge is more complete and our technique in identification perfected, furnish interesting and valuable criteria regarding conditions under which rocks and veins were developed.

BINARY SYSTEMS

Perthites are intergrowths of at least two solid solutions; sometimes the number of phases present is more than two. The number

[1] H. E. Merwin, *Jour. Wash. Acad. Sci.*, Vol. I (1911), p. 59.

[2] *Bücking Zeit. Kryst.*, Vol. VII, p. 566.

[3] Alling, *Jour. Geol.*, Vol. XXVIII (1921), pp. 209, 275.

of minals present must be at least two, and it is conceivable that, with anorthite, celsian, etc., considered, the number may be as high as eight. But here we will confine ourselves to the potash-soda perthites.

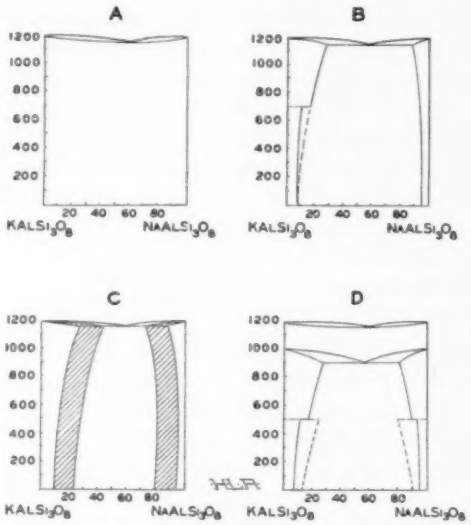

FIG. 1.—*A*. A thermal diagram illustrating the crystallization of γ feldspars only. After Dittler, *Tsch. Min. Petro. Mitt.*, XXI (1912), p. 513.

B. A thermal diagram illustrating the change in solubility of K-feldspar for Na-feldspar on inversion, after Vogt, *Tsch. Min. Petro. Mitt.*, XXIV (1905); XXV (1906); XXVII (1908), and Warren, *Proc. Am. Acad. Arts and Sci.* (1912), p. 513.

C. A thermal diagram showing non-equilibrium conditions where solubility is indicated by bands or zones instead of lines. After suggestions by Giolitti (Thum and Vernaci) *Heat Treatment of Soft and Medium Steels*. McGraw-Hill, 1921, p. 13 *et seq.*

D. A hypothetical thermal diagram, combining ideas shown in Fig. 1*A* and 1*B*, illustrating trimorphism; $\gamma \rightarrow \beta$ as a eutectoid change. The change in solubility upon $\beta \rightarrow \alpha$ inversion is shown (not thermodynamically) (1) by solid lines, a decrease in solubility and (2) by dashed lines, an increase.

Our knowledge at present is that the γ series, that is sanidine-barbierite, is a continuous series of solid solutions with a minimum (Roozeboom's Type III). The β series, orthoclase—albite, and the α series, microcline—analbite, are both discontinuous, eutectiferous series with limited solubility (Type V). If this, which is our present

conception, be true, then all phases in perthitic intergrowths are solid solutions and not pure minals. It is necessary to establish the solubility lines.

In the γ series the solubility lines coincide with the solidus, the lower concave line of the thermal diagram (Fig. 1A). In the β series the solubility lines are usually assumed to be more distant from the sides of the diagram (Fig. 1D) than is the case with the α series. That is, more of the soda minal may be dissolved in orthoclase than in microcline. Or, to state this conception in other terms, the potassium atoms (or ions [?]) in the orthoclase space lattice may be "proxied"[1] by albitic sodium atoms (ions [?]) to a less limited degree than is the case of the potassium atoms of microcline substituted by analbitic sodium atoms, without distorting the space lattice beyond the condition commonly called a single-phase system. On the other hand Winchell found that his data indicated that the reverse was true.[2] This conception is shown in Figure 1D by the dashed lines.

If this be true, and it seems to be a reasonable conception, it is possible that with the event of inversion the solubility changes are abrupt. The solubility lines in this case would experience cusps as Warren[3] has suggested (Fig. 1B). How pronounced these cusps are is a question to be settled in the future.

With falling temperature it is generally believed that there is a decrease in solubility. The solubility lines slope, that is they are not vertical, and are nearer the sides of the diagram at lower than at higher temperature (Fig. 1B).

SPECULATIONS ON THE THERMAL DIAGRAM

I have shown elsewhere[4] that the diversity of opinion regarding the thermal equilibrium diagram of the potash-soda feldspars is partly due to failure to recognize undercooling and non-inversion as a factor affecting the diagram. The relative stability of "metastable" solid solutions forces us to employ a series of diagrams to ac-

[1] Albert Johannsen, personal communication, 1921; *Jour. Geol.*, Vol. XXX (1922), p. 640; A. N. Winchell, *Amer. Jour. Sci.* (5), Vol. IX (1925), p. 312.

[2] Winchell, *Jour. Geol.*, Vol. XXXIII (1925), p. 719.

[3] Charles H. Warren, *Proc. Amer. Acad. Arts and Sci.*, Vol. LI (1915), p. 148.

[4] Alling, *Jour. Geol.*, Vol. XXXI (1923), pp. 287–89.

count for all K-Na feldspars. This compels us to consider that the genetic relation of all feldspars is paramount. In order to bring some order out of the present chaos, investigators need to discuss the origin and the thermal conditions which obtained during the formation of the specimens under investigation.

The lack of exact knowledge of the inversion temperatures of the various minals prevents the presentation of a satisfactory thermal diagram. I am fully convinced that it cannot be a simple one. The rate of cooling undoubtedly plays a fundamental part in the character of the resulting feldspars. Above a certain, and as yet an unknown, rate, γ feldspars, sanidine—barbierite and more especially sanidine, are carried to ordinary temperatures without inversion. At another rate, presumably a slower one, β feldspars, the orthoclase-albite series, result at normal temperatures. Perhaps it can be argued that at a still slower rate the α series, microcline—analbite, result. This, however, is without laboratory demonstration.

In addition to the above, the temperature from which these feldspars have been cooled or quenched is an important factor. Another probable factor is the change in the rate of cooling, best perceived in the form of cooling-curves. All I can say is that the laboratory work so far conducted does point to such a conclusion, but the details are not as yet available.

Furthermore, it cannot be denied that many feldspars have experienced reheating before being allowed to cool to the temperature of the earth's surface. Phenocrysts of potash feldspars in an extrusive magma undergoing differentiation by fractional crystallization may drift or sink into a hotter portion of the unfrozen liquid residue and there experience a rise in temperature, perhaps causing re-inversion and "magmatic corrosion." The same thing may occur when feldspathic sediments are assimilated or *lit-par-lit* injected by igneous matter. Although they may experience reheating and subsequent quenching, inversion to low temperature-modifications may not occur and the mineral may exist in the γ or β forms at room temperature. It does not follow that such feldspars would be stable for millions of years, for secondary inversion might take place after cooling. This is regarded as quite likely, but the phenomenon re-

quires definite proof. This seems to indicate that in spite of the high viscosity of the solid mineral, inversion may occur, especially when the feldspar is subjected to stress. But the rate of inversion may be so excessively slow, even in a geological sense, as to permit us to neglect it altogether.

One of the changes that undoubtedly occurs in the solid is the change in solubility of one phase for another, supposedly a decrease, causing a separation of a single phase into a system composed of two phases. Such a feldspar would be cryptoperthite, if the blebs of the separating phase are minute; perthite is easily visible. This change in solubility is shown by inclined lines in Figures 1B and 1D. I am convinced that α and β feldspars do not form at once two-phase systems by a change in solubility as the temperature falls, but may be carried to moderate temperatures without exsolution taking place. Such changes occur gradually. This means that a diagram to show this would not be an equilibrium diagram based upon an application of the phase rule. The need for a diagram is great, however, and hence I offer Figure 1C, which definitely attempts to show metastable conditions. The solubility changes are shown by bands occupying areas and not by lines. Within these bands, or solubility zones, a single phase is metastable, while perthite, which lies between the two zones, is stable.

A common conception of the term "anorthoclase" is that it is a potash-bearing soda feldspar,[1] presumably a single-phase system. Winchell still accepts this view.[2] I advocated a modification[3] in meaning, in spite of precedent of the original use of the term. "Anorthoclase" in my sense is α, β, or γ feldspar composed at least of the two minals ranging from $K–F_{70}Na–F_{30}$ to $K–F_{20}Na–F_{80}$, which exist as a single-phase system. If the views here suggested are correct, then γ anorthoclase is monoclinic, β anorthoclase may be monoclinic and triclinic, while α anorthoclase is triclinic. Only γ anorthoclase is stable, and that above 900°–950° C. range in temperature. I believe that there is sufficient evidence to entertain the view that

[1] Although Johannsen ("Microsc. Determ.," *Rk-Form. Min.*, 1922, p. 30) regards anorthoclase as a K-N feldspar.

[2] Winchell, *Jour. Geol.*, Vol. XXXIII (1925), p. 719.

[3] Alling, *Jour. Geol.*, Vol. XXIX (1921), p. 232.

many perthites are (1) the result of decrease in solubility attendant upon inversion (Figs. 1B and 1D), and (2) due to any form of anorthoclase, a single-phase system, becoming a two-phase system by exsolution.

But I am sure that there are other causes of perthites. I am surprised that petrographers in general have failed to note that some perthites exhibit lamellae or blebs of *two* generations. Warren[1] does speak of "the presence of very small lamellae, often exceedingly minute, in the microcline member . . . . " of a perthitic intergrowth, but he does not assign any specific genetic order to them. They are in my opinion due to inversion, to a eutectoid, and to inclined solubility lines. A few such feldspars that I have observed are listed in Table III.

TABLE III

PERTHITES OF TWO GENERATIONS

My No.	Label as Secured	My Name	Locality
630.....	Graphic granite	Microcline hypoperthite	Crown Point, N.Y.
977.....	Graphic granite	Microcline hypoperthite	Bedford, N.Y.
963a.....	Graphic granite	Microcline hypoperthite	Woodbury, Conn.
962.....	Oligoclase	Microcline hypoperthite	Verona, Ont., Canada.
974.....	Sunstone	Microcline hypoperthite	Delaware Co., Pa.
979.....	Microcline	Microcline hypoperthite	Valhalla, N.Y.
991.....	Orthoclase, var. Delawarite	Microcline hyperperthite Antiperthite	Lenni, Delaware Co., Pa.
995X....	Orthoclase	Microcline eutectoperthite	St. Lawrence Co., N.Y.
964.....	Amazonstone	Microcline hypoperthite	Mineral Co., Pa.
971.....	Amazonstone	Microcline hypoperthite	Florissant, Colo.
996.....	Orthoclase	Microcline hypoperthite	Unionville, Pa.
1148.....	Orthoclase	Microcline hyperperthite	Taxas, Pa.
1159.....	Orthoclase	Microcline hypoperthite	Kragerö. Norway.
1437.....	Cassinite	Cassinite	Blue Hill, Pa.

In case of a γ anorthoclase one set of blebs can be formed by inversion to the β modification and another set by inversion to the α form. There may be additional blebs due to exsolution which is brought about by a decrease in solubility upon falling temperature and change in pressure.

THERMAL EXPANSION OF ALKALI FELDERS

In a paper with the above title Kôzu and Saiki[2] record the changes in optical angle and the rate of expansion of various feldspars.

[1] *Proc. Amer. Acad. Arts and Sci.*, Vol. LI (1915), p. 138.

[2] S. Kozu and S. Saiki, *Sci. Rpts. Tohoku Imp. Univ.* (Ser. 3), Vol. II, No. 3 (1925), pp. 203–38.

On heating they show that at certain temperatures there are pronounced changes in these properties as shown by cusps in their curves. By taking the date presented in their table[1] I have constructed Figure 2A, which shows changes at various temperatures. There is a distinct range from 900°–950° and another from 650°–700°. At 500° perthitic lamellae dissolve on heating and exsolve on cooling

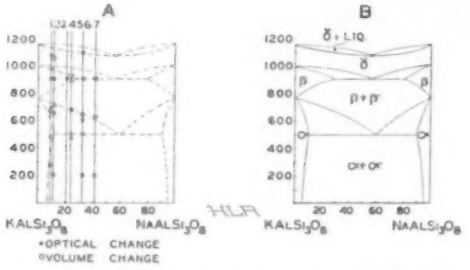

FIG. 2.—*A*. Plot of the cusps observed in curves of optical angle and thermal expansion of potash rich feldspars at various temperatures. Data taken from Kôzu and Saiki, *Sci. Rpts. Tôhoku Imp. Univ.* Ser. III, Vol. II, No. 3, 1925. Table XX, p. 235.

REFERENCE TO FELDSPARS

No.	Name	Locality	Composition, Mol Per Cent			Composition Assumed	
			K-Feld	Na-Feld	Ca-Feld	K-Feld	Na-Feld
1.....	Adularia	St. Gothard	88.3	9.3	2.4	90	10
2.....	Amazonstone	Pikes Peak	87.9	11.2	0.9	88	12
3.....	Sanidine	Eifel	76.9	21.8	1.3	78	22
4.....	Moonstone	Ceylon	73.5	23.9	2.6	75	25
5.....	Orthoclase	Arendal	66.6	32.8	0.6	66	34
6.....	Moonstone	Korea	61.0	33.7	5.3	66	34
7.....	Perthite	Japan	56.1	42.7	1.2	57	43

The dashed diagram represents a hypothetical thermal diagram devised as a suggestion to show trimorphism of potash-soda feldspars by eutectoid relations.

B. The thermal diagram of 2*A* with stability fields labeled.

gradually. The lowest change, 200°–275°, is reported as faint and is not fully understood.

The origin of perthitic blebs due to inversion from γ anorthoclase to β perthite may be attributed to the presence of a eutectoid. As

[1] S. Kozu and Saiki, p. 235, Table XX.

the actual diagram is not available and is not likely to be forthcoming in the near future, I venture to offer a diagram based upon the results of Kôzu and Saiki which is obviously speculative (Fig. 2B). In its construction I have secured, I believe, much that is helpful in understanding perthites and, what is perhaps more important, have appreciated along what lines further investigation should be carried on. Kôzu and Saiki do not suggest any such application of their results, hence I assume the responsibility in this matter. Combining the results obtained by Merwin with those of these Japanese investigators, I conclude:

1. That inversion from γ to β feldspars occurs, when time allows, during a range in temperature from about 980° down to 900° C;

2. That inversion from β to α feldspars occurs, when the rate of cooling is slow enough, during a range in temperature from about 750° down to about 650° C.

REFRACTIVE INDICES

Previous investigations[1] have shown that each series, α, β, and perhaps the γ, possesses its own set of values for indices of refraction. Winchell's recent diagrams have carried the matter further than my own studies. In Figures 3A, B, and C I have reproduced them with slight modifications based upon findings of my own. The solid lines are more or less established, the dashed lines interpolated, and the dotted lines inferred. The great difficulty in constructing these curves lies in the paucity of reliable data and the discounting of the effect of $CaAl_2Si_2O_8$ invariably present. Hence those curves are of limited value as means of determining by microscopic means the composition of natural potash-soda feldspars.

It must be realized that the indices of refraction of γ and β feldspars are the values of metastable minerals at room temperatures. We have no way of knowing as yet how perfectly the γ and β feldspars retain their characteristics when undercooled. Apparently the inversion from one modification to another is sluggish and does not

[1] See Winchell, *Jour. Geol.*, Vol. XXXIII (1925), pp. 720, 722; also Alling, *Jour Geol.*, Vol. XXXI (1923), pp. 360, 361.

entail a very profound change in the space lattice. It may even consume considerable time, and hence a given specimen may consist of two modifications, that is, of two phases. What effect this condition would have on the indices is problematical. It may or may not be cumulative in effect. It will thus be seen that Winchell's relatively

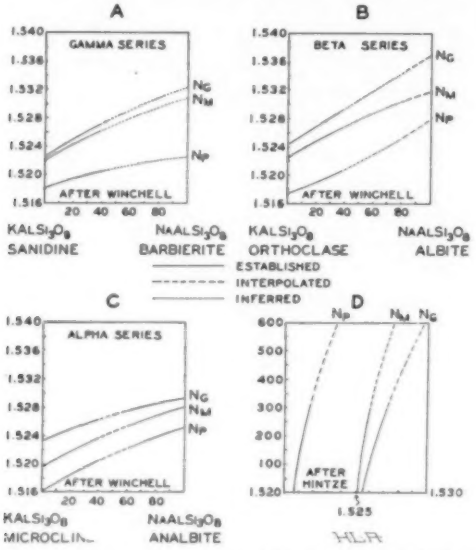

FIG. 3.—*A*. Indices of refraction of the γ-feldspars, sanidine-barbierite, at normal temperatures. After Winchell, *Jour. Geol.* XXXIII (1925), pp. 714–27.

B. Indices of the β-feldspars, orthoclase-albite, after Winchell.

C. Indices of the α-feldspars, microcline-analbite, after Winchell.

D. Effect of temperature upon the indices of refraction of Sanidine from the Eifel (San_{75}, Bar_{25}). Data from Hintze, *Handb. Min.* II, p. 1349. Used in constructing Fig. 4.

simple curves are of less practical value than mineralogists and petrographers wish they were.

The indices as a rule rise with temperature.[1] The coefficient of index for temperature stated as so much per degree is not reliable for great ranges in temperature. In Figure 3D the change in indices is given for sanidine from the Eifel.[2] The relation of index to tempera-

[1] While that of the usual index liquids falls.

[2] Data from Hintze, *Handbuch der Mineralogie*, Bd. III, s.s. 1349.

ture is shown by three curves: one for each optical orientation of the specimen, all for sodium light. If this specimen is in a metastable state, which is here assumed, the significant figures would be at tem-

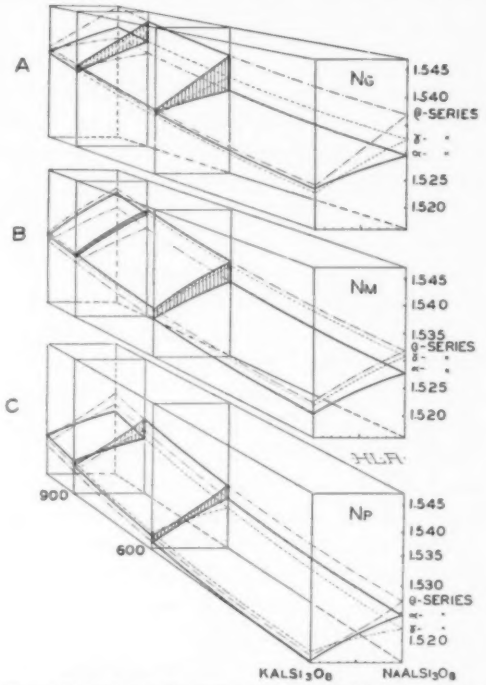

FIG. 4.—Three dimensional diagrams showing possible effect of inversions upon indices of refraction of potash-soda feldspars. The three axes: horizontal, composition; vertical, value of index; longitudinal, temperature. The four vertical planes; from left to right: 1000° C., 900° C., 600° C., and normal temperatures.

A. Index surface for Ng orientation.

B. Index surface for Nm orientation.

C. Index surface for Np orientation.

peratures between 900° C. and the incongruent melting-point, and not at the temperature of the laboratory.

I have been unable to secure data for the construction of many index-temperature curves, hence I am forced to offer in Figure 4 a highly speculative diagram. Here it is assumed that inversion from

γ to β forms and from β to α forms occurs with the proper rate of cooling. Furthermore, it is assumed that approximately the same increase in index for temperature of the sanidine from the Eifel with a change in temperature from zero to 300° C. obtains from 300° up to the incongruent "melting-point" and for the β and α feldspars as well.

The significance of this admittedly complicated and speculative diagram is that it shows the need of obtaining laboratory proof of the presence or absence of the cusp surfaces at the temperature of inversion through index-temperature curves. Any lack of continuity at these critical inversion temperatures may be interpreted as highly suggestive of inversion.

In case of the failure to invert due to undercooling, the index surface for room temperature may be secured by carrying the surface of that modification, by interpolation, down to that temperature. If this is done for Np, Nm, Ng values of the index of the γ and β metastable modifications together with the stable α forms, Winchell's diagrams are thus secured (Figs. 3A, B, and C). In reality, of course, I have used the reverse process and worked back from Winchell's diagrams to my three dimensional diagrams.

Actually the diagram shown in Figure 4 is still incomplete, since the *rate of cooling* has been ignored. If the fourth dimension were really available, the rate of cooling could be introduced. This factor would influence the index surfaces something after the following manner. When the rate is sufficiently slow I assume the presence of cusp surfaces that are vertical as in Figure 4, indicating complete inversion at a given temperature (γ–β and β–α). When the rate is more rapid the cusps become steep slopes; when fast, gradual slopes; when extremely rapid, the cusps disappear entirely. In this last case the index surfaces are extended to normal temperatures, preferably as dashed lines, indicating metastable conditions.

Of course the above discussion presupposes the presence of three series, which I am calling the α, β, and γ series. The actual knowledge we possess regarding them is in large measure confined to the potash-rich ranges. Under ordinary laboratory conditions it is very difficult, if not impossible, to assign a soda-rich feldspar to a definite series.

DIAGRAM OF WINCHELL

Winchell has presented in a recent diagram[1] a very suggestive summary of our knowledge of the potash-soda series. He shows the incongruent melting of $KAlSi_3O_8$ after Morey and Bowen[2] (see Fig. 5), the melting-point of $NaAlSi_3O_8$ after Bowen,[3] the minimum melting-point between the end-members after Dittler,[4] and the stability limits of the various phases present. For the β series he suggests, in the text, that the solubility lines be fixed at $Or_{70}Ab_{30}$ and $Or_{10}Ab_{90}$. But his diagram shows otherwise. It must be remembered that these solubility lines are inclined and hence single limits fail to convey the proper idea.

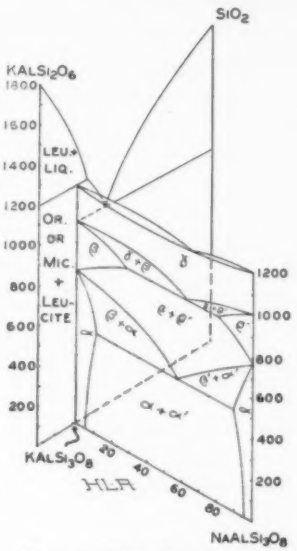

FIG. 5.—Two diagrams linked together: Thermal diagram of the $KAlSi_2O_6$–SiO_2 system after Morey and Bowen, *Am. Jour. Sci.* (5), IV (1922), pp. 1–22, showing interminallic compound $KAlSi_3O_8$ and my hypothetical diagram (Fig. 2*B*) of the $KAlSi_3O_8$–$NaAlSi_3O_8$ system. Introduced to show incongruent melting of $KAlSi_3O_8$.

Winchell[5] says, "The gap in the third [α] series is commonly regarded as still greater [than the β series], but according to data collected for this study it is much less, namely from about $Or_{80}Ab_{20}$ to about $Or_{40}Ab_{60}$. He suggests that this is due to the fact that both microcline and analbite are triclinic, but he has failed to show it in his diagram. I would criticize his use of symbols. Instead of $Or_{80}Ab_{20}$ (orthoclase and albite) I would either use $K\text{-}Feld_{80}Na\text{-}Feld_{20}$ or $Mic_{80}Anab_{20}$ in order to be consistent with the theory of polymorphism here assumed to be correct. Winchell

[1] Winchell, "Studies in the Feldspar Group," *Jour. Geol.*, Vol. XXXIII (1925), p. 719.

[2] *Amer. Jour. Sci.*, Vol. CCIV (1922), p. 1.

[3] N. L. Bowen, *Amer. Jour. Sci.*, Vol. CLXXXV (1913), p. 577.

[4] *Tsch. Min. Pet. Mitter*, Vol. XXXI (1912).

[5] *Jour. Geol.*, Vol. XXXIII (1925), p. 719.

furthermore fails to bring out the metastable nature of anorthoclase by introducing it in the same diagram along with perthite. I have already suggested[1] that anorthoclase is potentially perthite through the intermediate stages of cryptoperthite and microperthite. This is supported by the work of Foerstner,[2] Dittler, Kohler,[3] and myself.[4]

It takes a series of diagrams to show all potash-soda feldspars.[5]

MOUNTAIN'S OBSERVATIONS

Mountain[6] found that there was no natural classification of the anorthoclases, potash oligoclases, oligoclases, etc. which he studied. This is not at all surprising, as we are dealing with solid solutions and therefore perfect gradations exist. Hence any classification must be artificial.

Mountain reached the conclusion that there was no indication of several series of feldspars due to polymorphism. A survey of Mountain's paper indicates that the specimens studied have had similar origins and hence probably belong to a single series. Mountain has not emphasized the fact that different rates of cooling and the temperature from which the feldspars have cooled has an important bearing on this question.[7] Judging from my curves (surfaces)[8] I am inclined to believe that his curves for extinction angles, specific gravities, and index of refraction Nm[9] are for the "triclinic" series. In this paper I would refer them to the α series; α microcline, α anorthoclase, α analbite, α potash-oligoclase series. Mountain apparently did not have any γ or β feldspars. Hence I question his justification

[1] Alling, *Jour. Geol.*, Vol. XXIX (1921), pp. 224–26, 233, 235, 291, paragraph 13; *Jour. Geol.*, Vol. XXXI (1923), p. 373.

[2] H. Foerstner, *Zeitschr. f. Kryst.* (1884), p. 333.

[3] E. Dittler and E. Kohler, *Anz. Akad. Wiss. Wien.* (1924), pp. 61, 101–2, 153–54.

[4] Alling, *Jour. Geol.*, Vol. XXXI (1923), p. 355.

[5] *Ibid.*, pp. 288, 373–74.

[6] E. D. Mountain, *Min. Mag.*, Vol. XX (1925), pp. 331–45.

[7] See Alling, *Jour. Geol.*, Vol. XXXI (1923), p. 287.

[8] *Ibid.*, pp. 360–61.

[9] I am employing Np, Nm, and Ng following Winchell and the French School instead of α, β, and γ for the three indices to avoid confusion with the three series modifications, here assumed to be due to polymorphism.

in saying: "This would indicate, then, that so-called 'microclinic' and 'triclinic' modifications of the same chemical composition are not dimorphic (allotropic) modifications, but that they differ only in the coarseness of their twinning, submicroscopic or very fine twinning giving rise to an apparent cleavage-angle of about 90°."[1] He refers to Mallard and Michel Lévy's classic statements.[2] Although Mountain is in excellent company, I believe he was unfortunate in having no representatives of the β and γ feldspars in his collection. His data consist of only sixteen specimens. I can readily appreciate the difficulty of securing data on a sufficient number of feldspars for an investigation of his kind.

Mountain's figure for the index Nm, for K-Feld$_{65}$ Na-Feld$_{35}$ feldspars (Nos. 1–2), as read from his curve,[3] is approximately 1.525. Winchell's value for the same index and composition is approximately 1.527, which is sufficiently close. Mountain's No. 1 is from Pisto Scuso, Sardinia, and taken from a paper by Fouque.[4] Winchell's No. 8 has the same locality and reference; hence I assume it to be the same feldspar. The significant thing is that Winchell refers the Porto Scuso feldspar and the anorthoclases from Pantelleria to the microcline-analbite series, my α series. I conclude therefore that Mountain has insufficient data to judge upon the number of series within the alkali feldspars.

If the anorthoclases from Pantelleria are phenocrysts in porphyritic, vitreous, and aegirite pantellerites and trachytes[5] and hence cooled rapidly, how is it that they are α feldspars, stable only at low temperature? Microscopic study of my own slides[6] show that some are essentially zonally-grown cryptoperthites, while others are soda microclines and potash analbites. Anorthoclase, in the sense generally used, does not constitute a large percentage of the phenocrysts

[1] E. D. Mountain, *Min. Mag.*, Vol. XX (1925), p. 340.

[2] Mallard, *Ann. des Mines*, Vol. X (1876), p. 10; Michel Lévy, *Bull. Soc. Fr. Min.* Vol. II (1879), p. 135.

[3] Mountain, *op. cit.*, p. 340, fig. 9.

[4] *Bull. Soc. Fr. Min.*, Vol. XVII (1894), p. 409.

[5] H. S. Washington, *Jour. Geology*, Vol. XXI (1913), pp. 653–70, 683–713; Vol XXII (1914), pp. 16–27.

[6] Specimens 1125, 1126, 1127, and 1129.

of the rocks from this famous island. They exhibit characteristics typical of numerals which have changed following crystallization. I believe that these feldspars are now mainly in the α condition owing to inversion after crystallization. The peculiarity is that while inversions have occurred, some specimens are still in the process of inversion. That is, some appear to be polyphase feldspars in the process of inverting. Hence the reliability of these as illustrations of α feldspars is questionable.

SUMMARY

1. The potash-soda feldspars appear to be composed of at least two end-members, each of which may be trimorphous.

2. The three potash-feldspar minals are assumed to be:

γ $KAlSi_3O_8$	Sanidine
β $KAlSi_3O_8$	Orthoclase
α $KAlSi_3O_8$	Microcline

3. The three soda-feldspar minals are assumed to be:

γ $NaAlSi_3O_8$	Barbierite
β $NaAlSi_3O_8$	Albite
α $NaAlSi_3O_8$	Analbite

4. The Millard–Michel Lévy theory of submicroscopic twinning is capable of explaining cleavage angles of 90° and extinction angles of microcline and orthoclase.

5. Such a theory does not disprove polymorphism. These two theories are independent of each other.

6. The Millard–Michel Lévy theory is not capable of explaining the thermal inversions noted by Des Cloizeaux and by Merwin, nor the cusps in the thermal expansion curves of Kôzu and Saiki, nor my findings in the specific gravity and indices of refraction curves. The theory of polymorphism will explain these phenomena.

7. Inversion from one modification to another is so sluggish as to require a long time, hence I question whether Kôzu and Endô held their specimen at high temperature for a sufficient length of time to secure inversion. I do not grant that a failure to find a marked difference between Laue-diagrams of orthoclase and microcline disproves polymorphism. Vogt has accepted Hadding's Laue-diagrams as disproof of polymorphism, while Winchell and I do not.

8. Winchell's curves of γ and β potash-soda feldspars are for metastable, quickly cooled feldspars. Curves for stable forms should be given above the inversion temperatures. At normal temperatures they have less significance. His curves are based upon the necessary assumption that the γ and β potash-soda feldspars are single-phase systems and not solutions and mixtures of two modifications.

9. Classification of the potash-soda feldspars still awaits proper treatment. Winchell's further subdivision of the plagioclase feldspars is most complete and in strong contrast with the meager classification of the potash-soda series.

GUNNISON TILLITE OF EOCENE AGE

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ABSTRACT

The Gunnison tillite was first described in a paper presented by the present authors at the 1924 December meeting of the Geological Society of America. Further geologic and physiographic field studies have established a somewhat widespread distribution of this formation and appear to justify a close correlation with the Ridgway tillite of mid-Eocene age.

Gunnison is located in a small, irregularly shaped valley lowland in the midst of the Rocky Mountains of Colorado (Fig. 1). It is about 130 miles in a straight line southwest from Denver. To the east are the Sawatch Mountains; to the south, the Cochotopa hills; to the southwest, the San Juan Mountains; to the west, a plateau region, into which the Black Canyon of the Gunnison has been cut; and to the northwest and north are the Elk and West Elk mountains.

Our attention was first called to certain exposures of the tillite near Gunnison by A. P. Coleman, of Toronto University. At the close of the 1924 field season the authors visited the area and made further discoveries that led to the presentation of a short paper at the Ithaca meeting of the Geological Society of America. The following summer of 1925, the junior author revisited the area, located many additional and somewhat widespread outcrops, made a comparative study of the Eocene drift at Ridgway, Colorado, determined the geologic relations of the Gunnison formation, and thus established the ancient origin of this tillite.

PHYSIOGRAPHIC SETTING

The lowland parklike area in which the town of Gunnison is located is surrounded by hills that rise several hundred feet above the valley bottom. This relationship can best be seen on the accompanying relief map and in Figure 7. Beyond these hills that immediately surround the Gunnison lowland are the present mountain

ranges, which are remnants of a former much mightier group of ranges that existed at the opening of the Tertiary period. It is quite possible that the earlier mountain areas extended to points nearer the Gunnison valley lowland than do the ranges of today.

The glaciers of the Pleistocene did not reach this area. This is evidenced by the fact that the nearest Pleistocene moraines are some 10 miles distant from the town of Gunnison, and the majority of them much farther away.

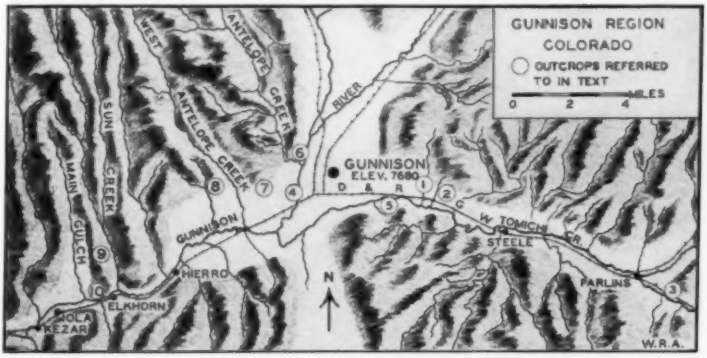

FIG. 1.—Index map of the Gunnison region

THE GEOLOGIC SETTING

The rock formations cropping out most frequently and characterizing much of this portion of the country are those of the pre-Cambrian complex. These rocks are chiefly gneisses, granites, mica schists, phyllites, and basic intrusions. While these outcrops are numerous, they are almost entirely restricted to the area south of Gunnison, along Tomichi Creek to the east and the Gunnison River to the west. From Hierro westward through the Black Canyon the Gunnison is cutting into this ancient fundamental complex. To the east and northeast of the town of Gunnison the hills are composed chiefly of Dakota sandstone. At a few localities the overlying Mancos shale is present. The Tertiary volcanics spread over much of the area to the west and northwest and are found overlying the tillite at many localities both east and west of the town. The valley lowland

is filled with outwash material from the high mountainous regions to the north and east. Much of this is undoubtedly Pleistocene glacial outwash.

DESCRIPTION OF THE TILLITE

In each of the twenty or more outcrops of the tillite that were discovered and studied most of the material was distinctly unas-

FIG. 2.—Type locality three miles east of Gunnison near state highway. The Gunnison tillite is here mantled by volcanic tuff.

sorted. A few pockets or lenses of water-worn pebbles and cobblestones were seen. In contrast to the overlying volcanic tuff, the tillite is considerably lighter in color (Fig. 2). It ranges from a light brown buff to a light gray. With but one exception, the tillite is well consolidated. It contains many bowlders as large as 4 feet in diameter, an abundance of cobblestones, and a body of fine sands and silts which fill in the places between the larger stones. Subangular forms are very common among the stones of the drift, and many specimens were found that are clearly striated (Fig. 5). The formation is distinctly and conspicuously, both physically and lithologically, heterogeneous.

It contains specimens of granite, gneiss, schist, quartz, porphyry, diorite, basalt, felsite, greenstone, slate, phyllite, quartzite, sandstone, and conglomerate. At some of the outcrops of the tillite, especially at Parlins, the granitic and gneissic specimens are remarkably weathered. Here bowlders 3 and even 4 feet in diameter are so disintegrated that the picks and shovels used in widening the roadway have cut through these huge bowlders instead of dislodging them. In fact some of these stones are so completely weathered that they may be crumpled in the hands.

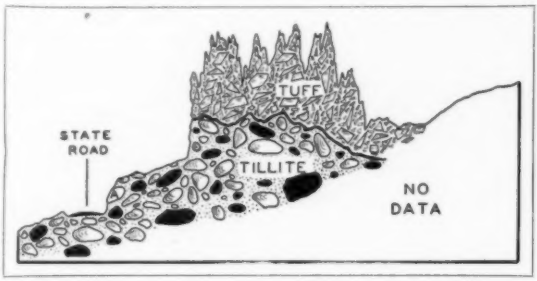

FIG. 3.—Diagrammatic section within the area of the type locality. (*A*) marks the position of the large striated bowlder shown in Figure 5.

LOCATION I. TYPE LOCALITY

Three miles east of Gunnison along the state highway is found the type locality of Gunnison tillite (Figs. 2 and 3). At this location both the tillite and the volcanic are well cemented and stand in bold cliffs or sharp pinnacles. They might first attract attention because of their Hoodoolike forms, and a glance from the auto road might easily lead one to call the entire outcrop a volcanic tuff. The larger fragments in the overlying tuff range up to 3 feet in diameter. Much of the volcanic material is angular, dark brown, and andesitic. The finer débris which serves as a cementing material in the tuff is of a grayish-brown color.

At this locality the tillite exposes all the usual physical characteristics of an unstratified glacial deposit (Fig. 4). No evidence of water work was observed. Striated stones and bowlders were common, and the specimen illustrated in Figure 5 was secured at this

outcrop. Although at this particular location the base of the tillite is not exposed, the drift is probably resting on Dakota sandstone.

FIG. 4.—Near view of the Gunnison tillite at the type locality

FIG. 5.—Striated stones secured at the type locality

Large angular fragments of the sandstone are found in the glacial formation. At another locality a little farther east the tillite rests immediately upon the Cretaceous sandstone.

The upper surface of the tillite is clearly defined at the type locality, as shown in Figure 2. At many points it is possible to put your finger on the contact line separating the volcanic tuff above from the glacial till below. There was no soil detected at the surface of the tillite nor any evidence found of surface weathering preceding the deposition of the tuff. The absence throughout the area of any indication of a period of weathering following the deposition of tillite and preceding the accumulation of the tuff suggests that the period followed promptly upon the retreat of the ice.

LOCATION 3, NEAR PARLINS

Along the state road just east of the Parlins railway station an excellent outcrop of the more highly weathered tillite was discovered. At this exposure the drift was not covered by tuff, and consequently the material has been completely weathered. In contrast to many of the localities where water action has been effective, the Parlins outcrop is a perfect example of an unstratified till with material ranging all the way from fine sands and silts to bowlders 4 feet in diameter. Figure 6 shows the relationship of the tuff to the tillite. It is quite possible—in fact very likely—that the tillite has been at some time entirely covered by the volcanics.

LOCATION 5

On the south bank of Tomichi Creek, a short distance east of Gunnison, there is an excellent exposure (Fig. 8). It resembles very much the type section, but large bowlders are not common, and few striated stones were found.

The base of the tillite, although not clearly exposed, probably rests on pre-Cambrian rocks that outcrop at frequent intervals on the south bank of the creek.

LOCATION 6. THE PALISADES

Just west of the town of Gunnison are the Palisades (Fig. 7). While these bold bluffs appear at a distance to be entirely composed of volcanic tuff breccia, on a closer examination numerous exposures of tillite were discovered. Most of the material in the glacial débris at this locality is distinctly rounded and smoothed by water action, but nevertheless it yielded a number of well-striated stones (Fig. 9).

The relationship of the two formations at the Palisades is such as to suggest that the glacial débris rested on a hillside, possibly a valley bluff, at the time when the volcanic fragments were settling

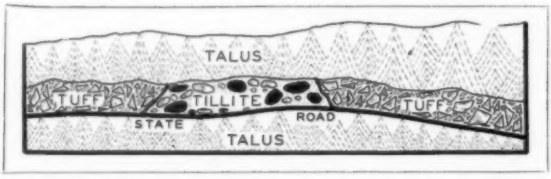

FIG. 6.—Diagram of relations as exposed in a road-cut at location No. 3, near Parlins.

FIG. 7.—The Palisades at the west margin of the lowland near Gunnison. The bold bluffs are composed chiefly of volcanic tuff breccia, but at many points at this locality the underlying tillite is exposed.

through the air. It is fair to assume that the glacial drift was not at that time as much consolidated as at present, and as the load of ejectamenta increased in volume, landslides probably occurred. There are vertical contacts at this locality which indicate that slip-

ping and faulting may have occurred. At a number of places between the tuff and the tillite there is a zone of transition of a few inches in thickness that may be accounted for by heavy rains falling during the accumulation of the first volcanic débris.

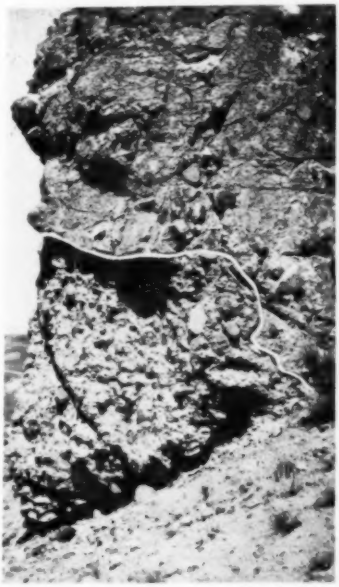

FIG. 8.—View taken at location number 5, where contact of underlying tillite and overlying tuff is sharply defined.

FIG. 9.—Detail in the contact between the Gunnison tillite and overlying volcanic tuff at the Palisades. (Locality 6.)

LOCATION 8

Most of the area west of the town of Gunnison is covered with the volcanic-tuff breccia, and only when the streams cut far into the volcanics does the underlying tillite appear. In the volcanic débris angular fragments from 8 to 10 feet in diameter are not uncommon. Figure 10 shows location 8, where a very large body of this tuff-capped tillite appears in steep bluffs on the side of a small valley. Much of the material at this location is well water worn, and dis-

tinctly striated stones are therefore rare. Many of the diorite gabbros and granites are completely weathered and may be crumbled in the hands.

AGE AND CORRELATION

The general geologic conditions throughout this part of Colorado indicate that a long period of deposition was brought to a close at

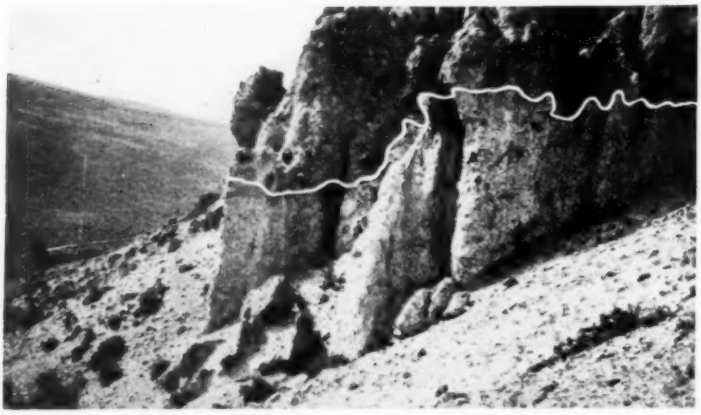

FIG. 10.—A large body of the tillite as exposed at locality number 8

the end of the Mesozoic era by a great physical revolution during which the ranges of the Rocky Mountains were formed. The dissection of the uplifted areas must have continued contemporaneously with the orographic movements. The higher areas were dissected into mountain forms, and hundreds, perhaps thousands, of feet of sediment were removed from the region about Gunnison where the tillite under consideration has been discovered. Over considerable areas near Gunnison the entire sedimentary section has been removed, exposing at the surface the pre-Cambrian complex.

The earlier generation of Rocky Mountains must have been the source of the glaciers that advanced into the Gunnison lowland. By

the opening of the Oligocene these ranges were entirely removed, and a broad peneplain spread over the entire southwestern portion of the state. At no time since mid-Eocene have there existed any ranges comparable in elevation to those in this earlier generation of Rocky Mountains.

The Pleistocene glaciers which formed in the present generation of mountains in this vicinity failed to reach the Gunnison region. They were much smaller glaciers than those that deposited the tillite.

When the question of age is approached through a study of the overlying formations the all-important question is the geologic age of the volcanic-tuff breccia of the Gunnison region. No paleontological evidence has been discovered, but here again the physiographic history of the region leads to significant conclusions. The present valleys, which are excavated into and through the volcanic tuff, are of late Pliocene and Pleistocene age. This forces the conclusion that the volcanic tuff itself is of still greater age. This evidence does not, however, make it clear how much older than the mid-Pliocene the tuff may be.

Turning now to a comparative study of the condition in the Ridgway district where Eocene tillite was discovered in 1913,[1] we find striking similarities which suggest a close correlation of the two bodies of ancient till. These localities are 50 miles apart. In each district the drift rests upon the eroded surface of a Cretaceous formation and is overlain by volcanic-tuff breccias. In character and in magnitude the tuff breccias are similar, and are quite different in character from the mid-Tertiary tuffs of the San Juan or West Elk mountains. In the San Juan district the age of the overlying volcanic-tuff breccias has been determined to be Eocene. Through physiographic studies of this same area it would appear that this tuff was of late Eocene age.

CONCLUSION

Through a study of the lower contact and the general topographic and physiographic relations during early Tertiary time it

[1] W. W. Atwood, "Eocene Glacial Deposits in Southwestern Colorado," *U.S. Geol. Survey Prof. Paper 95-B*, 1915.

appears that the Gunnison tillite is probably of mid-Eocene age. Through a study of the upper contact it is certain that the tillite is older than mid-Pliocene. From a comparative study of the two localities of Tertiary tillite in this part of the state it is reasonable to infer that the glaciers that deposited these formations descended from high mountain areas at about the same time. At Ridgway, the evidence of mid-Eocene age is conclusive, and therefore the most reasonable conclusion is that the Gunnison tillite is also mid-Eocene.

FURTHER INVESTIGATIONS OF THE ROCKY MOUNTAIN TRENCH

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ABSTRACT

This paper discusses the geology of the Rocky Mountain trench and the ranges east of it between the towns of Lake Windermere and Golden. The structure is complex, with much isoclinal folding and thrust-faulting. A comparative study is afforded by cross-sections of the Beaverfoot-Brisco ranges. A series of transverse faults have helped produce some intravalley ridges, but were not important in developing the trench. A huge breccia, several hundred feet thick and miles in extent, is found at many places along a vertical bedding-plane fault which probably has several miles of displacement. Part of the Rocky Mountain trench has a horst type of structure, rather than the *graben* structure which has been suggested by others.

INTRODUCTION

In pursuance of a plan to investigate the origin and structural significance of the Rocky Mountain trench throughout its great length the writer returned to the southern portion in 1924 to clear up some puzzling features, left from earlier studies,[1] before carrying the investigations farther north into the geologically unexplored country. The features that were investigated particularly were (1) the intravalley ridges which are found within the trench floor north of Lake Windermere, and (2) the significance of the fairly constant deviation of the strike of the formations from the trend of the trench floor on the east side. While investigating these things more information was obtained concerning the general structure and stratigraphy of the Beaverfoot-Brisco ranges and of the adjacent valley of the Columbia River.

The Rocky Mountain trench has been described by a number of authors and hence no detailed description is needed in this article. Starting just south of the United States–Canada boundary in longitude 115° west, this valley extends northwest along the western

[1] F. P. Shepard, *Journal of Geology*, Vol. XXX, pp. 130–39 and 361–76.

side of the Canadian Rockies, separating them from several ranges on the west. It is remarkable both for its length of almost 1,000 miles and for its depth of from 3,000 to 10,000 feet. It is one of the longest linear depressions in the world. Most other very long valleys

FIG. 1.—A sketch contour map of the area considered. Partly based on topographic map of the Canadian survey. Contour interval 1,000 feet. Level of Columbia valley approximately 2,500 feet.

are wider and less continuous, and their floors vary more in elevation. The Rocky Mountain trench has an average width of only about 4 miles, and so far as is known the elevation of its floor does not vary more than 1,000 feet.

TOPOGRAPHY OF THE AREA

The Canadian National Parks Topographic Maps include a part of the trench north and south of Golden. The rest of the region visited had only a regional map. Figure 1 gives an approximate idea of the topographic appearance of this section of the valley and of the surrounding ranges. The most striking physical feature of the region

FIG. 2.—Looking north along the Rocky Mountain trench, showing the intravalley ridges. Photograph by H. W. Gleason, courtesy of the *National Geographic Magazine*.

is the deep, mature valley of the Columbia River within the Rocky Mountain trench. Its well-graded flood plain is in striking contrast to the rugged mountains which rise abruptly on either side. The limit of the valley on the east is usually sharp, but on the west it is more irregular. Within the trench are some ridges surrounded on all sides by the valley floor (Fig. 2). The Beaverfoot and Brisco ranges look to be one and the same from the Columbia Valley, but the view from the Columbia-Kootenay watershed, near the juncture of these ranges, shows a difference between the two. The Brisco Range consists of three distinct ridges, the easternmost of which dies out

against the Kootenay Valley, leaving only two farther north in the Beaverfoot Range. The portion of the Beaverfoot Range between McMurdo and Castledale consists of only one main ridge, but the two ridges reappear farther north. As will be shown subsequently,

TABLE I

GENERAL SECTION OF THE FORMATIONS FOUND IN THE BEAVERFOOT-BRISCO RANGES

AGE	NAME	GENERAL CHARACTER	THICKNESS	
			Feet	Meters
Devonian Upper	Harrogate limestone (proposed)		600	182.9
Silurian	Brisco formation	Massive limestones, dark gray and black bands of graptolite-bearing shales	1,200 (Walcott)	365.8
Ordovician Richmond	Beaverfoot formation (Halysites limestone)	Massive limestones, partly dolomitic, gray to white. Intercalated layers of shale, sandstone, and quartzite	400–3,500	122–1,087
Ordovician	Wonah quartzite	Massive white quartzite, generally very pure	50–1,100	15.2–335.3
Ordovician Canadian-Chazyan	Glenogle shale (Graptolite shales)	Black shales containing graptolites and various thin-bedded limestones, sandstones, and shales	100–1,700	30.5–518.5
Lower Ordovician and Upper Cambrian (Ozarkian Walcott)	Goodsir Formation (Mons-Walcott)	Thin-bedded concretionary argillaceous limestones and shales, often much contorted	6,040 (Allen)	1,844
Upper Cambrian	Ottertail Limestone (Lyell-Walcott)	Massive limestone semi-crystalline magnesian	1,725 (Allen)	526

these topographic features are closely connected with the structure of the region.

STRATIGRAPHY

The accompanying table (Table I) gives a generalized columnar section of the strata found in the Beaverfoot and Brisco ranges. This is based partly on the excellent section made by Walcott at

Sinclair Springs.[1] The distribution of the formations is given in Figure 3. This map probably has inaccuracies due to difficulty in differ-

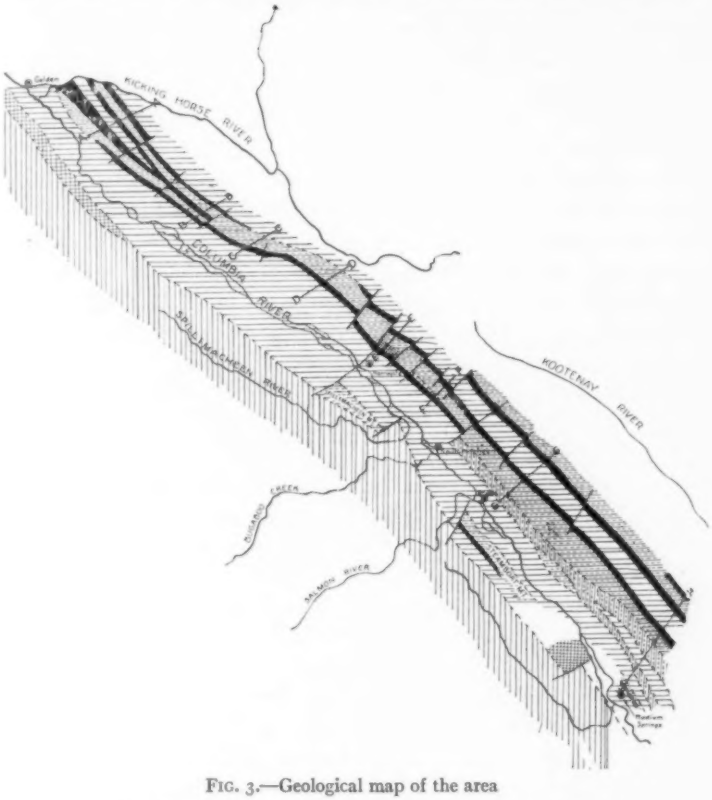

FIG. 3.—Geological map of the area

Devonian
Silurian (Brisco)
Ordovician, Richmond (Beaverfoot)
Ordovician (Wonah quartzite and Glenogle shale)
Lower Ordovician and uppermost Cambrian (Goodsir formation)
Upper Cambrian (Ottertail limestone)
Pre-Cambrian

entiating between the Richmond Beaverfoot and the Silurian Brisco formations, and because of the few exposures of rock along

[1] C. D. Walcott, *Smith Miscellaneous Collections*, Vol. LXXV, No. 1, pp. 1–51.

the trench floor. Also, faults are numerous and could not be entirely traced in the time available. Sections made by Allen[1] at the north end of the Beaverfoot Range, and by Walcott[2] at the south end of the Brisco Range, show lithologic and stratigraphic similarities of the formations, but considerable differences as regards their thickness. Walcott uses different names in all instances from those proposed by Allen, but tracing the formations between the two sections shows them to be the same, or at least very similar, throughout the entire length, and therefore the writer, in conjunction with Dr. Walker, of the Geological Survey of Canada, is giving precedence to the names used first, except that such names as Glenogle shale, named from the town Glenogle, and Beaverfoot limestone are preferable to the names Graptolite shale and Halysites formation and have been accepted along with Walcott's Wonah quartzite, which is a very persistent formation formerly incorporated by Allen in the Halysites limestone.

THE OZARKIAN AND RICHMOND FORMATIONS

Following the lead of Ulrich, Walcott has made use of the term Ozarkian for the age of his "Mons" formation (Goodsir of the present writer), and he also considers the Richmond as belonging to the Silurian period. The writer does not wish to enter into the controversy in regard to the Ozarkian, but Walcott's reasons for putting the Richmond in with the Silurian perhaps deserve some comment here. He argues that the presence of a quartzite beneath the (Beaverfoot) Richmond in this region, as well as beneath the Richmond dolomites of Utah, suggests a physical break at this horizon which is absent between the Richmond and the overlying, Middle Silurian, Brisco formation. The quartzite is said to show the initial beach sands of the transgression of the Richmond seas. Since there is a larger break between the Lower Ordovician and the Richmond than above the Richmond he believes the boundary of Ordovician and Silurian is properly placed below the Richmond.[3] As to the correctness of the interpretation of the quartzite as a beach sand when

[1] J. A. Allen, *Geol. Survey of Canada Guidebook No. 8*, Part II, Plates 67–186.

[2] C. D. Walcott, *loc. cit.*

[3] C. D. Walcott, *op. cit.*, pp. 41–44.

it is in places 1,100 feet thick, there should be room for debate, but even if there is a larger break below the Richmond than above it at this locality, there are many parts of the world where the opposite is true. A recent paper by O. T. Jones[1] compares the American and British Ordovician-Silurian boundary and shows that the Richmond is much more closely related to the Ordovician than to the Silurian. If the practice of dividing periods on the basis of their local or regional unconformities were followed generally, the boundaries between the various periods would cease to have any time significance, because the various sedimentary breaks in one region are often quite different in time from those in other regions or other continents. In order to avoid chaos it seems as though paleontology alone should be relied upon to determine the limits of the various systems.

STRUCTURE

That the Rocky Mountain trench is located along a zone of intense deformation has been stated previously.[2] This is most strikingly shown in the bordering zone of the Beaverfoot and Brisco ranges. The folds are dominantly, although not entirely, isoclinal. In many of the sections that are well exposed along the tributary valleys the dip of the formations hardly varies more than a few degrees from vertical, except where cut by faults.

The sections shown in Figure 4 give an idea of the structure, although they are drawn on too small a scale to show all the details. Comparison of these sections shows some progressive changes in the intensity of deformation. In general the structure is simplest in the middle sections (C and D), becoming more complex both to the north and to the south. The most southerly section (H) is by far the most complex.

The folds may be traced best by referring to the synclines. Section A shows four rather small synclines which are shown to have contracted into two in Section B and which in Section C appear to have undergone further contraction. In D we see chiefly the left side of one syncline, while in E there has been a shift of the axis of this syncline, and the right side forms the crest of the range while

[1] O. T. Jones, *Journal of Geology*, Vol. XXXIII, pp. 380–88.

[2] F. P. Shepard, *op. cit.*, pp. 130–39.

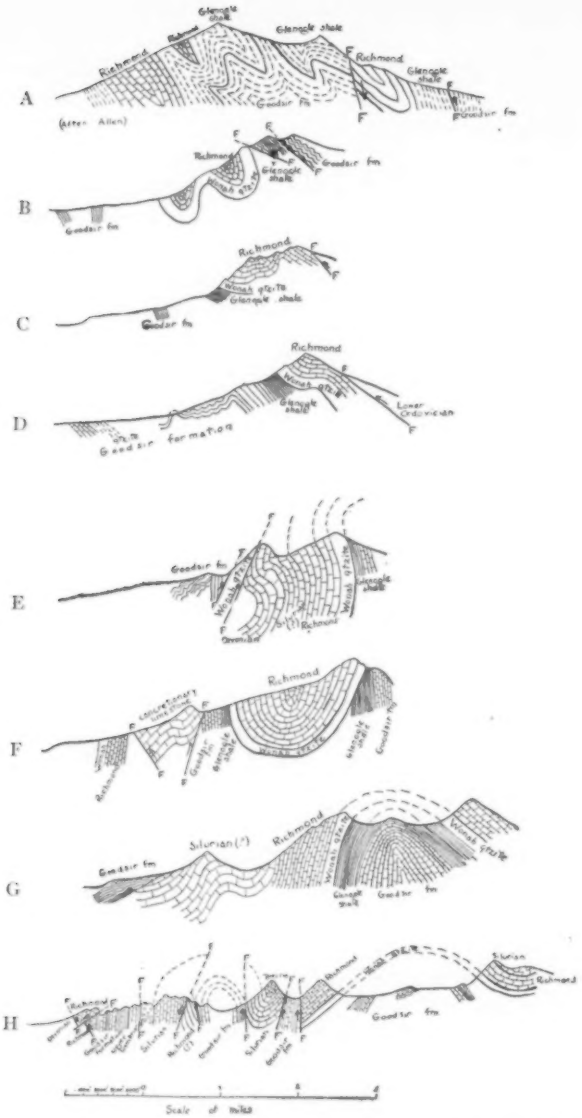

FIG. 4.—Sections across the Beaverfoot and Brisco ranges. Their location is shown in Figure 3.

the left side is cut off by a fault. In Section F both sides of this syncline appear with the right side still forming the crest of the range. Just to the south of the locality shown in Section F the extra ridge cited above comes into the range from the east, and in

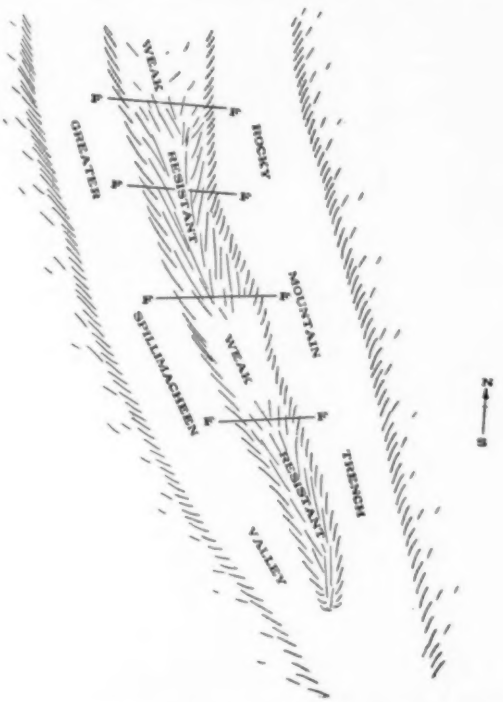

FIG. 5.—Showing the preglacial ridge between Spillimacheen Valley and the Rocky Mountain trench.

this ridge, as shown in Section G, the other limb of the eastern anticline appears. Also in this section the syncline becomes less pronounced and an anticline comes in to the west. In the Sinclair section (Section H) this anticline is probably still present as is also the syncline, but they are both complicated by the intense faulting of the west part of the section.

TRANSVERSE FAULTS

Abrupt changes in the sections.—The rather marked difference in the east-west position of the syncline in sections D and E is due to a transverse fault. A number of such faults will be noted by referring to the geological map of the area (Fig. 3). The presence of these faults was indicated also by two other features: (1) the intravalley ridges, previously mentioned, have abrupt north and south terminations; (2) the folds on the east side plunge persistently northward, but without an accompanying progressive change in the age of the formations.

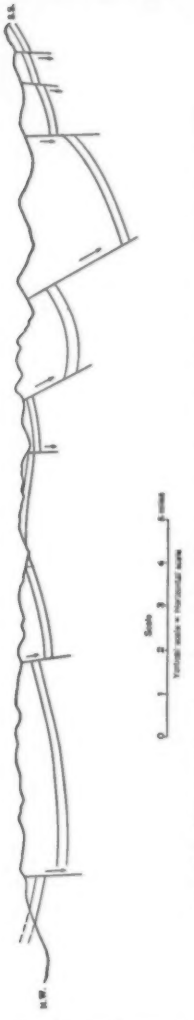

FIG. 6.—Showing the deformation of the Wonah quartzite along the axis of the Beaverfoot Range

The intravalley ridges.—The principal ridges found within the trench can be seen plainly in Figure 2. Steamboat Mountain, the ridge with two peaks in the center of the view, rises 2,500 feet above the valley floor. This mountain is in part an outlier of the Richmond formation (Ordovician) which is found in many places in the range that borders the trench on the east. There is a distinct transverse fault at the northern end of this mountain. Both transverse and longitudinal faults bound other ridges of the valley group, suggesting that they are fault-block mountains. However, since the upthrow sides of the faults now form the low parts of the relief, these mountains are actually erosion remnants due to the superior resistance of the rock of which they are made.

At one time the left side of the trench shown in Figure 5 was part of a large tributary valley coming in from the northwest, separated from the trench by a mountainous ridge. This intervening ridge contained transverse faults which, because of offsets, caused portions of it to be less resistant than the rest. Glaciers

coming down the tributary valley, as well as down the trench from the north, overflowed this ridge, cutting away its weaker portions. This caused the two valleys to coalesce in places, leaving the resistant parts standing isolated above the valley floor.

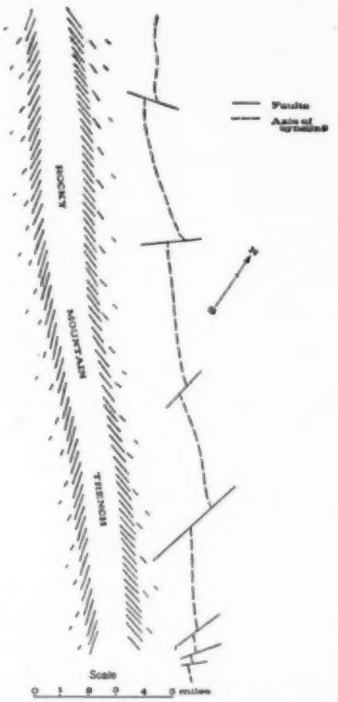

FIG. 7.—Showing the shifting of the axis of a syncline by the transverse faults

The north-plunging folds.—In traveling along the trench floor casual observation would give one the impression that the formations on the east side dipped gently to the north. More careful study would show that this apparent dip was only the pitch of the folds. Such a northerly pitch would be expected to cause the formations to increase in age going south along these ranges, but no such change is found. The explanation for this situation was found by tracing the strike of the formations along parts of the crest of the Beaverfoot-Brisco ranges. A series of faults cutting transverse to the axis of the

range were discovered. These cause the formations to be repeated and to persist along the range in spite of the northerly pitch.

Figure 6 shows somewhat diagrammatically the apparent deformation of a prominent bed along the range on the east side of the trench from McMurdo to Spillimacheen. In some places there is a series of small faults in close proximity that are too small to be shown in this section. Since it is not usual to make sections parallel to the long axis of a range, it is difficult to say whether this section is characteristic or unusual. There is a striking resemblance here to some of the east-west sections across the basin ranges of Nevada. The Tertiary and post-Tertiary normal faulting in the Great Basin is

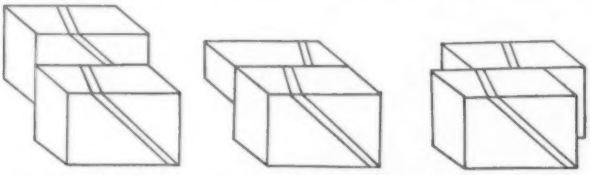

FIG. 8*a*.—Showing how the apparent displacement may be the same after erosion in either a vertical or a horizontal shift fault.

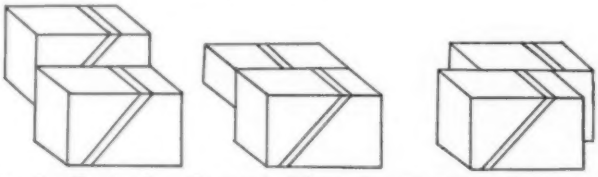

FIG. 8*b*.—Showing how the case is different from that above if the dip of the formation is reversed.

generally thought to show a horizontal extension of the surface. However, there is perhaps reason to question whether these faults along the trench are so much of the normal type as they are horizontal shift faults with only apparent vertical displacement. A ground plan showing the shifting of the axis of a syncline by these transverse faults (Fig. 7) suggests horizontal displacement. This can be tested theoretically, as in Figure 8, which illustrates in section *a* how, with the dip in the proper direction, vertical and horizontal displacement may have similar appearance after erosion. However, in section *b*, where the dip of the formation is reversed, with other conditions remaining the same, the result is a change in direction of the offset

of the vertical fault. By comparison with the range under consideration, where both east- and west-dipping beds as well as vertical beds are displaced by the faults, it should be possible to interpret the character of the faults. If the faults had dominant vertical offset they would show apparent horizontal offset in different directions according to the dip. The displacement, as shown in the ground plan (Fig. 7), is in each case in the same direction, despite the dip of the beds. Therefore the faults probably have dominant horizontal displacement.

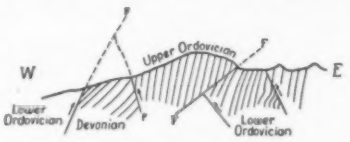

FIG. 9.—Faults in Sinclair Canyon

Probably these faults, with their horizontal shift, were at one time a cause of considerable irregularity in the eastern wall of the trench. This irregularity is still seen to some extent, but has undoubtedly been much decreased by the vigorous glacial erosion during the Pleistocene.

FAULTING NEAR SINCLAIR SPRINGS

The series of complex faults which occur to the west of the Hot Springs in Sinclair Canyon on the Banff-Windermere road deserve some special consideration. These faults are shown in Figure 9. With the exception of the one farthest to the west, the actual fault planes are exposed in each instance. These faults were first discussed by the writer,[1] and since then by Walcott,[2] but in neither case was their full significance appreciated because neither the presence of the Devonian nor that of the Lower Ordovician on the west was discovered. The section gave all appearances of ending to the west with the Richmond, at what is known as "Gates of the Canyon," but in a rather obscure part of the Sinclair stream bed, farther down than the Canyon entrance, a fine section of Devonian was discovered by the writer in 1924. The amounts of stratigraphic displacement of these faults cannot be figured with much accuracy with data available at present, but, roughly considered from left to right, they are as follows: 3,400, 1,200, 300, 2,700. These figures are the more im-

[1] F. P. Shepard, *op. cit.*, p. 135.

[2] C. D. Walcott, *op. cit.*, p. 11 and Plates 5 and 6.

pressive when one considers that the distance across the section is only a few hundred yards.

Greater magnification of a part of the section shows a confusing variety of faults (Fig. 10). Undoubtedly there are some inaccuracies in this last section, since the beds are not sufficiently distinct to be matched up in all cases on both sides of the faults.

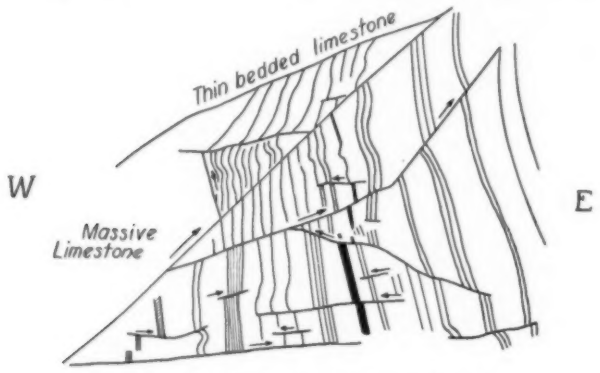

FIG. 10.—Magnification of a portion of Figure 9

THE REDWALL FORMATION, A REMARKABLE BRECCIA

General character.—Extending along the Brisco and Stanford ranges for at least 15 miles there is a brecciated formation of very unusual type. This formation was given the name of Redwall breccia by Walcott,[1] who considers it to be a fault breccia. In places its thickness is as great as 250 feet. It consists of a mass of limestone bowlders ranging in size up to about 7 feet in diameter, and varying in color through different shades of red, yellow, brown, gray, purple, blue—in fact, almost every color is represented, and in places seven or eight different colors within a few feet. The general color of the formation is either red or yellow. The cement is almost entirely calcium carbonate with occasional crystalline development of calcite. In some places it appears to consist chiefly of vein material. Rarely the breccia contains stratification. This is generally very much contorted and extends for only a few feet.

[1] Charles D. Wolcott, *op. cit.*, p. 11 and Plates 3 and 4.

Relations to other formations.—The most striking thing about the breccia is its relationship to the other beds. In the vicinity of Sinclair Springs it has all the external appearance of being a part of a continuous, comfortable series of rocks (Fig. 11). On the east is the Brisco formation of Silurian age with vertical stratification running parallel to the breccia. On the west the Ottertail (Lyell) formation, which is probably of Upper Cambrian age,[1] is also roughly parallel to the breccia. There are about 6,800 feet of formations missing in this section, making the evidence for a fault overwhelming in spite of this parallel arrangement. The breccia continues to the south, at least six or seven miles, with the same vertical wall appearance and separating formations of distinctly different ages. East of the town of Windermere, in the Windermere map area, there are several zones of this breccia, and in some cases the type of formation on both sides of it is very similar, making the evidence for faulting in such places somewhat doubtful. In the Sinclair section, 1½ miles east of the main breccia formation, there is another breccia (Fig. 4, Sec. H) on the side of the mountain north of the road. This occurs in what is probably a syncline, and it has the same stratigraphic position as the other breccia. Eight miles north of Sinclair in the same syncline there is a huge mass of brecciated limestone, probably from 400 to 500 feet thick. This differs from the main mass farther south in that its contact with the underlying formation, while probably conformable, is not a vertical one. In the southernmost outcrop that was found the breccia cut across the bedding planes for a short distance.

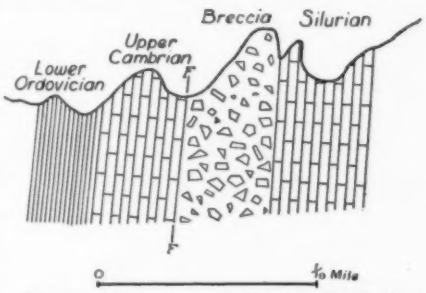

FIG. 11.—Section just east of Radium Hot Springs, Sinclair Canyon.

Formerly considered as "possible Silurian tillite."—The large bowlders in the breccia and its apparent interstratification with other layers led the writer to suspect that it was a Paleozoic tillite.

[1] C. D. Wolcott, *op. cit.*, p. 39.

The finding of a real tillite in direct line of continuation with the breccia and ressembling it to some extent strengthened this supposition and led to the publication of a short paper on the subject.[1] The evidence as given in this paper is probably correct as it stands, but further evidence obtained in the 1924 season makes it clear that the real tillite is not the same as the breccia, in spite of its juxtaposition and resemblance in some cases. The real tillite was found to overlie with marked unconformity the rock involved in the post-Cretaceous folding of the region. It is evidently of quite recent origin and probably represents some Pleistocene till which has been firmly consolidated by ground water charged with lime.

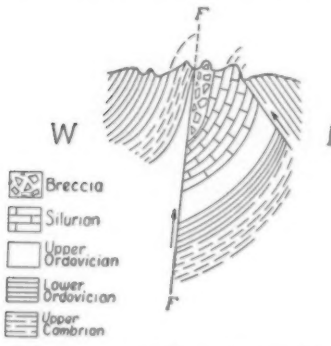

FIG. 12.—A possible explanation of the bedding-plane fault of large displacement in Sinclair Canyon.

Present views concerning the origin of the formation.—Of course in the zones where the breccia occurs along faults it can be explained as a result of the differential movements and the accompanying friction. However, its thickness of hundreds of feet seems somewhat incompatible with this idea. In positions where it is not along faults, or at least where faulting is of minor importance, it is difficult to explain. It may be that one of the Silurian formations, or several of them, are made up of brittle limestone of a thin-bedded variety differing considerably in colors. The tremendous pressures which have been applied to the rocks in the zone from Brisco to Lake Windermere may have largely reduced this formation to a breccia. The writer knows of only one other locality where complete brecciation on such a large scale occurs. In the extreme western end of the Sudbury area in Canada (Township 105) Quirke found a breccia in the pre-Cambrian which is several hundred feet thick and may have relations similar to that just described.[2]

[1] F. P. Shepard, "Possible Silurian Tillite in Southeastern British Columbia," *Journal of Geology*, Vol. XXX (1922), p. 77.

[2] T. T. Quirke, personal communication.

A vertical bedding-plane fault of large displacement.—There are many cases of bedding-plane faults, but as a rule these are difficult to recognize because of the normal bedding relations on either side. In the case of great overthrusts, like the Lewis thrust, great changes in formation occur along faults which are in places essentially bedding faults, but these are low-angled faults and have many miles of throw. The case at Sinclair, where there is a tremendous displacement along a bedding fault in vertical layers, is possibly unique. How the structure continues underneath in order to develop these

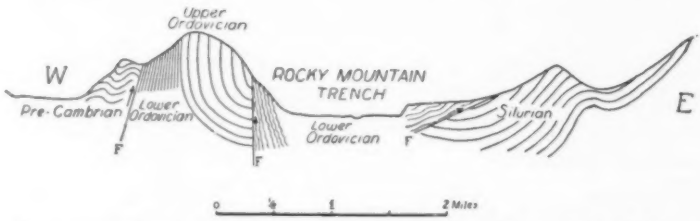

FIG. 13.—Section of the Rocky Mountain trench at a point just south of Brisco

relations is not an easy problem. The accompanying section is an attempt to suggest a possible explanation for such a feature (Fig. 12). When one considers that the vertical relations of the beds along the fault continue for miles, over ridges and down into valleys, and that the amount of stratigraphic hiatus is easily 6,000 feet, the amount of displacement on this fault undoubtedly amounts to several miles. Perhaps it is even comparable with the largest vertical faults in the world.

THE INTRICATE FOLDS WITHIN THE TRENCH

The Goodsir formation, consisting chiefly of shales with some thin-bedded limestones, is shown on the accompanying map (Fig. 3) as occurring chiefly in the vicinity of the Rocky Mountain trench, and to a slight degree in the mountains. Practically all of the outcrops of this formation and of the Cambrian formations within the trench show much plication. To the north, along Canyon Creek, this highly folded condition can be traced west for a mile to the massive quartzite of the pre-Cambrian. On the east side of the trench the same sort of deformation is present as far east as the Richmond limestones of the Beaverfoot Range. The massive formations of the

Richmond are in striking contrast to the plicated members, being involved only in the major folds of the region. It would seem from comparison as though the shortening within the shaly formations of the Beaverfoot was greater than in the more massive underlying and overlying formations, but it is difficult to see how this could be, if the same lateral forces deformed the whole mass. There are two other possibilities, either that there has been more deformation in the zone where the shales occur, i.e., within the trench, or that the shales have been much contorted in some zones and pinched out in others.

THE HORST WITHIN THE TRENCH

The *graben* origin for the trench suggested by Daly[1] was combatted in an earlier article by the writer.[2] The findings of the 1924 season leave little doubt but that the supposition of a *graben* is erroneous, at least for the part of the trench under discussion. Referring to the map, we find the Goodsir formation forming the floor of the trench practically everywhere. The formations on the east are for the most part younger, and in a few places, as in Steamboat and Spillimacheen mountains (ridges in center of map, Fig. 1), the rocks of the west side of the Columbia Valley are younger than those within it. These relations are just the opposite of what would be found in the case of a *graben*, and suggest a horst. On the east side of the trench, as shown in several of the cross-sections, a fault accounts for the older formations within the trench. There is, in all probability, also a fault on the east side of Steamboat Mountain, making the section at this point like that in Figure 13. This forms a horst, the fault on the east, however, being a thrust instead of the usual normal fault found in textbook diagrams of a horst. The presence of a deep valley instead of an elevated tract along the horst is certainly unusual. It is no doubt due to long-continued erosion which has exposed the weaker underlying formations, changing an uplifted area into a depression.

That much of a tremendously long depression like the Rocky Mountain trench should be located along a horst would seem re-

[1] R. A. Daly, *Geol. Survey of Canada No. 38*, p. 600.

[2] F. P. Shepard, *op. cit.*, p. 131.

markable, but in this connection it is interesting to note that in a *reconnaisance* of the Omenica-Finlay rivers, 400 miles farther north along the same trench, McConnell[1] found the same general relations of older rock within the trench and younger on each side. The significance of this horst remains for future investigations to determine.

Acknowledgments.—The writer wishes to acknowledge the able assistance in the field of Mr. H. B. Willman; and for the determination of fossils he is indebted to Professors T. E. Savage and P. E. Raymond. The co-operation of Dr. J. F. Walker, of the Geological Survey of Canada, in the same region was also much appreciated. Professor T. T. Quirke was of great assistance in revising the manuscript.

[1] R. G. McConnell, *Geol. Survey of Canada, Annual Report*, Vol. VII, Part C (map).

NOTES ON THE TIDAL PHENOMENA OF BAY OF FUNDY RIVERS[1]

E. M. KINDLE[2]
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ABSTRACT

The phenomenon of bubbling sometimes seen at the surface of estuarine and other waters and often ascribed to natural gas is discussed. The large sand waves at the mouth of the Avon River are described. The tidal waves in the Petticodiac River are described in detail. The color of sediments deposited by the tides is discussed, and the results of a bacteriological study of Bay of Fundy muds by Dr. G. B. Reed is given. The conclusion is reached that the black color of certain beds of black mud is the result of chemical changes induced by bacteria.

The ecology of paleontology as it develops should be aligned with comparative studies of such strongly contrasted modern seaways as the current-swept bottom of the Bay of Fundy and the current-free area of the Irish Sea southwest of the Isle of Man. The channel between Ireland and the Isle of Man, although subject to a spring-tide rise of more than 18 feet, is reported to remain perfectly tranquil. In such an area of marine serenity the conditions of life and sedimentation must differ vastly from those which characterize the Bay of Fundy and its estuaries. The exceptional opportunities offered by the Bay of Fundy, with its 60-foot tides, for the study of sea-bottom conditions will be apparent if it is contrasted with the nearly tideless Gulf of La Plata in South America, which is of comparable shape and size. The vast areas alternately covered and laid bare by the tide about the estuaries of the rivers entering the Bay of Fundy disclose much which is instructive to the geologist who wishes to improve his interpretations of the older rocks.

During the summer of 1925 the writer was able to revisit, after an interval of eleven years, the estuaries of certain Bay of Fundy

[1] Published with the permission of the Director, Geological Survey of Canada, Ottawa.

[2] Dr. G. B. Reed, of Queen's University, has contributed the bacteriological note (pp. 651–52) on the estuarine muds.

rivers. The resulting observations are recorded in the following notes, which relate chiefly to phenomena attendant upon the rise and fall of the tides.

EFFERVESCENCE

Fishermen and others having an intimate acquaintance with the estuarine waters of the Bay of Fundy are familiar with a vigorous bubbling of the water, sometimes ascribed to the escape of natural gas, which occasionally occurs over limited areas as the tide rises. This phenomenon, which apparently happens at very irregular intervals, has been observed twice by the writer. In one case where the opportunity to observe it at close quarters was excellent, the bubbling was of a rather violent character comparable with that which accompanies the boiling of water, and extended over several square feet of surface. In this case the effervescence occurred in shallow water which was covering a sand-bar and continued for several minutes. The escaping gas was doubtless air which, having penetrated the partially dried sand or the burrows of minute marine creatures below it, was temporarily imprisoned in the sand by the rapidly rising water till the increasing pressure drove it out. Vaughan Cornish has recorded comparable observations in describing the bore of the Severn, where he speaks of the imprisoned air in the suddenly covered sands spurting through the seething waters.[1] In some cases the contact of cold sea-water with sun-heated sand-bars might result in freeing sufficient CO_2 to produce effervescence at the surface. Certain plants which grow under water have been observed to generate oxygen so rapidly that the minute bubbles actually gave rise to a musical tinkle.[2] Air and gases of either organic or inorganic origin may at different times be responsible for the effervescence sometimes seen on the surface of the estuarine waters of the bay, and by some assumed to represent natural gas.

Whatever the source of gases producing bubbling at the surface may be, their escape from the bottom sediments is apt to produce small irregular shaped pits which would be filled in many cases by

[1] Vaughan Cornish, *Waves of the Sea and other Water Waves* (Open Court Pub. Co.), p. 249.

[2] B. W. Evermann and W. H. Clark, *Lake Maxinkuckee, a Physical and Biological Survey*, Ind. Dept. of Conserv., Vol. II, p. 119.

sediment carried by the incoming tide and sometimes permanently preserved. Some of the perplexing markings on consolidated sediments may have a genesis directly connected with effervescence, or the escape of gases from bottom deposits.

SAND-WAVES AND "SPLIT BARS"

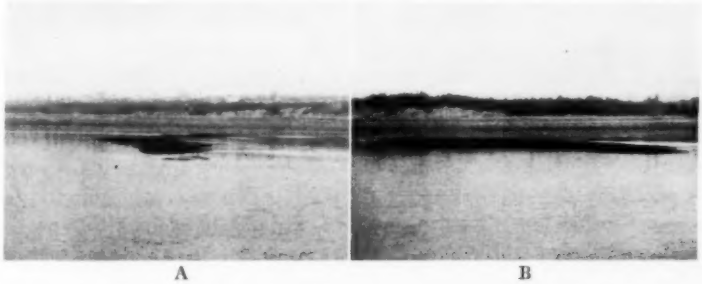
Photographs of the bed of the Avon River taken by the writer in 1914 immediately above the wagon bridge at Windsor, Nova Scotia, show the sand-waves, or meta-ripples, and the kettle-structure which characterized the surface of the big sand-bar directly above and below the Canadian Pacific Railroad bridge at that time.[1] An inspection of the same locality twice repeated during the past summer shows that the sand-waves and irregular depressions indicated by the photographs of eleven years ago are not now formed at this locality. Instead, the ebb tide now leaves a flat sand-bar marked only by ordinary asymmetrical ripple-mark. Since the 1914 photographs were taken, the completion of the new C.P.R. bridge has added a third set of piers to the river bed at Windsor. The slight reduction of current velocity which must have resulted from placing a third set of piers in the river just above the old piers seems to be the most probable reason for the disappearance of sand-waves from the surface of the bar between the bridges.

At low tide in midsummer, the channel of the lower 10 miles of the Avon River is a broad, nearly waterless belt of sand-bars, from ½ to 3 miles wide, bordered by mud flats. Rocky bottom interrupts the sand and mud deposits for considerable stretches on the west shore, where occasional ribbon-like strips of sand less than a yard wide and a few hundred feet long indicate short stretches of relatively slack current. The sand-bars show no tendency to depart from the long, broad, flat, generally ripple-marked type, except at one locality.

Opposite Horton Bluff light on the eastern side of the channel, nearly opposite the mouth of Mill Creek, the structures known locally as "split bars" occur. These are sand-waves, or meta-ripples, of much larger size in the case of the larger examples than the writer

[1] See "Recent and Fossil Ripple Mark," *Bull. 25, Geol. Surv. Can.*, p. 19, Fig. B, Plate VIII.

has seen elsewhere. They trend at right angles to the set of the tidal currents. The sand-wave belt has a length of about $\frac{1}{3}$ of a mile and a maximum breadth of about 300 yards. The material is largely sand, but a percentage of gravel is present in upstream bars, and occasional bowlders occur between the larger bars. The spacing and height of the sand-waves vary greatly and to a degree not observed in fresh-water river "split bars" or sand-waves. The upstream bars are, in general, higher than those lower downstream. One of these is about two feet higher than any of the others. This is clearly evident in the early stages of ebb tide. The majority of the downstream



A B

FIG. 1A, B.—Upper part of two sand-waves uncovered by ebbing tide, Avon River, N.S., opposite Horton Light.

sand-waves have a width of 15 feet or 18 feet on an average, and a height of 1 to $1\frac{1}{2}$ feet, but the larger sand-waves rise 7 or 8 feet above their troughs. Most of these large "waves" drop off downstream in a series of small stairstep terraces or "waves" of slight width, 2 to 5 feet, often giving a high degree of irregularity of topography of the downstream slopes.

The larger "waves" are, according to fishermen, permanent throughout the summer. The occasional presence of living barnacles and bryozoa on large stones between larger bars seems to verify this statement, for such fixed forms of life would be destroyed by continuous shifting of the sand-waves under the influence of ordinary tidal currents. The looseness and softness of the sand in some of the smaller waves, however, clearly indicate reformation of some of the minor features of the "waves" with each tide. The permanent form

for the season, as regards the larger sand-waves, is probably given during the spring floods, and during the exit of the 15- or 20-foot bed of ice which is reported to cover most or the whole of the river in winter with a mass of broken blocks. The highest sand-waves begin to emerge when the tide is about three-fourths out. The entire emergence takes place in calm weather without any rip or special current-wave development. The covering likewise proceeds very quietly on a calm day. Windy weather would no doubt create more turbulence over the sand-waves than elsewhere.

The tops of two of these bars in the early stages of emergence are shown in figures 1*A* and 1*B*.

TIDAL WAVES

The Petticodiac River presents the most spectacular tidal feature of any of the Bay of Fundy rivers. The steep-faced wave called the bore, which initiates the upstream flow of the tide, was observed four times during the summer at Moncton, New Brunswick, which is probably the best point for its study. The river at Moncton is about 1 mile wide. At ebb-tide a wide expanse of sand, with a negligible amount of water bordered with mud, forms the visible bed of the channel. The approach of the foaming wall of water 2 to 4 feet high is an imposing sight, and can be seen several minutes before it reaches the observer (Fig. 2*A*). A steadily increasing roar of the rushing water-front precedes its arrival, which reminds one of the sound of a large bowlder rapid in a northern stream. It passes with a swash distinctive of the bore, resulting from the churning up of the sand and mud, which are absent from ordinary rapids. A series of waves, spaced at 10 or 12 feet, follow directly behind the bore (Fig. 2*B*). About 5 or 6 minutes after the bore has passed, the surface is broken by waves 10 or 12 feet apart and about 1 foot high over parts of the midstream bars. As these subside after a short interval, the roar of similar waves forming at other points is heard, the sound of violent rapids momentarily increasing or decreasing and shifting from point to point in the wide channel of the river. After the advancing water has covered the sand-bars to a depth of about 3 feet, a series of standing waves form with amplitude of about 6 or 8 feet. These persist about five minutes and then begin to break down-

stream. The breaking phase passes into a smooth-water phase, each of the three phases having approximately a five-minute period, one succeeding the other after that interval, till the water has reached a

A

B

FIG. 2A, B.—The bore and the waves which immediately follow it, Moncton, N.B.

depth of 8 or 9 feet, at which the bottom drag fails to generate waves. The tawny brown color of the sediment-charged water is a feature of the bore consequent on the violent wave- and current-action which follow it.

The unusual feature of waves breaking in a downstream direction, or the reverse of that in which they are moving, was observed also at Windsor in waves accompanying the first stages of the upstream tidal flow. From the Wentworth wharf at Windsor, the initial advance of the tide is seen to be accompanied by strong waves spaced 10 to 18 feet apart. Some of the higher ones were observed to break downstream.

The breaking of waves over considerable areas of the mud and sand bottoms of the tidal rivers as the tide comes in, combined with the strong currents, stirs up the soft sediments and gives the water a soupy consistency quite inimical to the forms of marine life which live in comparatively clear water. Dredging which was done in 1914 between Indian Point and Hantsport brought up only empty shells. But living mollusks were found in abundance below Chivirie Point, which may be regarded as the mouth of the river, where bay and river-channel waters merge and carry a smaller percentage of sediment.

COLOR OF INTERTIDAL SEDIMENTS

The writer's observations indicate that the color of the fine sediments in the tidal river estuaries of the Bay of Fundy is controlled to a large extent by the character and color of the glacial drift in the regions drained by them. Around the Avon River estuary for example, the Carboniferous limestones and the preglacial red soils which they have supplied them have given a decidedly red color to much of the till deposits. This is distinctly reflected in the brown color of the sediments of the intertidal zone about the mouth of this stream. The Bear River, in southwestern Nova Scotia, traverses a region in which the drift shows no reddish color whatever, and its intertidal sediments at the mouth likewise show no trace of brown or red. Gray, blue, drab, and various shades of brown are the colors which generally characterize the intertidal sediments of the Bay of Fundy. Coal black sediments are found, however, at certain localities wherever an abundance of vegetable matter has been present during the deposition of sediment. Salt-marsh plants have been found in abundance at the few localities where black sediments have been observed. The following section measured on the east bank of the Avon River

just below the St. Croix, furnishes an example of black mud sandwiched in between chocolate brown and blue mud (Fig. 3*A*).

	Inches
1. Dull chocolate-colored clay	26
2. Black clay full of plant stems	13
3. Blue clay	20

Near Annapolis Royal at the mouth of the Lequille River, six or eight inches of black mud penetrated by numerous stems of marsh plants form the youngest bed of sediment and cap, a bed of drab clay sharply contrasted with it in color, but not otherwise differing from it (Fig. 3*B*). Figure 3*A* shows the marsh vegetation which appears to be an important factor in producing black mud. The occurrence of black sediments in stratigraphic association with beds of entirely unlike color, but having the same sedimentary origin, viz., tidal mud-flat deposits, indicates that sharp color contrasts may arise independently of any very notable changes in the conditions of deposition.

Two sealed glass jars of tide-flat mud which were secured from the Avon River at Windsor, Nova Scotia, developed changes in color, after standing for some weeks, which approximated the color differences observed in the sections at the mouths of the St. Croix and Lequille rivers noted above. One of the sealed jars was left in an office room having an average temperature of about 70° for two months, when it was found that the chocolate colored mud had developed innumerable small black patches, of various sizes and shapes, irregularly distributed through the brownish chocolate colored sediment. In some cases these could be seen to have as a nucleus a minute bit of plant-stem. In others the black patches were without visible nuclei. The second jar when unpacked, three months after collecting, showed a uniform blackening of the mud adjacent to the glass. The interior retained approximately the pale brownish color of the fresh Avon River mud. The bacteriological study made by Dr. Reed indicates that these changes in the color of the collected samples of Avon River mud, and the color contrasts observed in the sections at the mouths of the St. Croix and Lequille

rivers, are traceable to bacteria. The presence of salt-marsh vegetation may supply, in certain places, favorable conditions for the

A

B

FIG. 3.—(A) Sediments behind knife are black clay (2 of section page 649), Avon River, N.S. (B) Black sediments are now forming nearly at flood-tide level along margin of dike, Annapolis Royal, N.S.

bacteria which are considered to be the primary factors in changing brown or gray sediments in certain localities to black sediments.

BACTERIOLOGICAL FACTORS IN THE COLOR OF INTERTIDAL SEDIMENTS[1]

Bacteriological examination of jars of mud from the Avon River bed, referred to in the previous section, and from Bear River, Nova Scotia, together with freshly collected materials of a similar character from the intertidal zone near the mouth of the St. Croix River, at St. Andrews, New Brunswick, has yielded data which apparently account for the black color in certain of these deposits.

The black areas contain considerable amounts of sulphide, the red or chocolate areas contain little or no sulphide, as shown by qualitative tests, thus confirming the general view that such black colors are due to ferric sulphide. The red or chocolate color is itself ample evidence of the presence of iron. The origin of the sulphide and its irregular distribution in the deposits is less evident.

A culture study of these muds shows them to be heavily infected with bacteria of several species, those occurring most frequently being members of the aerobic genera *Proteus* and *Pseudomonas* along with various other aerobes particularly sporulating Bacilli and, less frequently, anaerobic *Clostridia*. One significant characteristic of most of these commonly occurring species is the production of hydrogen sulphide from proteins or sulphur proteins. The possible causal relationship of one of these hydrogen sulphide producing species was shown by introducing a pure culture of *Proteus vulgaris*, isolated from mud, into a medium containing protein, glucose, and dried and fused mud, bright red in color. After several days' growth there was a gradual blackening of the mud. Reference has already been made to the frequent occurrence of black patches in the mud about a nucleus consisting of a visible bit of plant stem. Such bits of organic material doubtless supply pabulum for the growth of bacteria to a much greater degree than takes place in regions of the mud free of organic substances, while at the same time the bacteria which are found to be present will split off hydrogen sulphide from plant or other organic remains.

Several conditions must be realized before the hydrogen sulphide can react with iron to form the black sulphide. The reaction will proceed only in a neutral or basic solution, and the bacterial

[1] Contributed by Dr. G. B. Reed.

protein decomposition which liberates hydrogen sulphide will ordinarily also produce ammonia or other bases, frequently in sufficient amount to render the surrounding medium distinctly alkaline. At St. Andrews, in any case, the surface sea water is slightly alkaline, pH 8.0 to 8.3. Hydrogen sulphide, however, reacts with extreme slowness with ferric oxide, so that before any considerable action can take place with the iron of the mud some chemical change is probably necessary. In the culture of *Proteus vulgaris* just referred to, the bacteria react more rapidly upon the carbohydrate than upon the nitrogenous substances, resulting in the formation of carbon dioxide and fatty acids, while later, as the carbohydrate is exhausted and the proteins are hydrolized with the liberation of ammonia and other bases, the solution becomes alkaline. This must result in the formation of at least traces of ferric hydroxide from the oxide. Hydrogen sulphide and ferric hydroxide readily react to form sulphide.

Under natural conditions in the marine deposits there are probably many other factors concerned in the solution of the iron. The production of carbon dioxide from bacterial action and from animal respiration is probably most significant. The frequent observation that the mud is blackest about clam or other shellfish beds is probably to be accounted for by action of carbonic acid on the iron followed by hydrogen sulphide production.

EVIDENCE OF ASSIMILATION AND ASSIMILATION PROCESSES

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In the Abstract of his paper on the "Evidence of Assimilation and Assimilation Processes" Mr. Bain states that he is here dealing with the general process of assimilation. His paper itself, however, treats in considerable detail of the Sudbury "norite-micropegmatite." Nowhere does he bring forward any satisfactory evidence for linking up these two subjects. The only feature of the whole Sudbury region to which he can point as giving him occasion to consider assimilation in this specific instance is "the mysterious absence" of sediments on one side of the igneous outcrop which occur on the other. Arguing on this basis we should consider that assimilation has been operative in the case of all dykes which have been intruded along a fault plane. In the case of the rocks at Sudbury, Knight[1] has already suggested that the whole Sudbury "basin" represents a down-faulted block. If this is true, the rocks met in the interior of the "Nickel Ranges" must be younger than those on the periphery. Again, Coleman[2] holds that the locus of the "norite-micropegmatite" intrusion has been a plane of unconformity, so that there could be no congruence between the material within and without the igneous outcrop. Whether these explanations are correct or not remains for more detailed field work to decide, but, in any case, either theory is to be preferred to an explanation based on assimilation of which absolutely no evidence is to be found in the rocks concerned.

In his treatment of this matter of assimilation Mr. Bain has adopted a most abstract method of approach. Neither assimilation nor any other theory of petrogenesis has its basis in physical chemistry, although it must conform to the laws of that science. It is fu-

[1] C. W. Knight, *Report Royal Ont. Nickel Com.*, 1917, p. 122.

[2] A. P. Coleman, *Report Ont. Bur. Mines*, Vol. XIV, Part III (1905), p. 10.

tile in geology to begin with the assumption of some chemical process and to endeavor to deduce a priori the field data which should result from its operation. As T. C. Chamberlin[1] found in his work on the origin of the earth, the method in hypothesis must be reciprocal: as he states, deduction must be guided by observed consequences and induction by discernible antecedents. It is in his failure to realize this principle that Mr. Bain errs when he dismisses, as having no value as criteria for assimilation, the presence of xenoliths and the occurrence of abnormal minerals in the igneous rock concerned. To banish these two features characteristic of the proved cases of assimilation is to miss entirely the significance of the theory of assimilation in petrogenesis. On the basis of abstract and purely physical-chemical laws there is no reason, as Mr. Bain states, why xenoliths should not be wholly dissolved and a homogeneous product result; but in the concrete science of geology there is the best reason in the world why we cannot allow this complete solution in magmas injected under these conditions, and that is, that we have no geological evidence of the process in similar rocks in similar positions in the crust. The same argument applies to his rejection of the presence of abnormal minerals as a criterion of assimilation. It seems to the writer, therefore, that in the case of the Sudbury sheet no sufficient reason has been brought forward for introducing the principle of assimilation to explain the occurrence of the norite and micropegmatite.

Passing now to the principles involved in the method brought forward by Mr. Bain for testing the amount of assimilation which has occurred in any magma, there are several features besides those already brought forward which both he and Mr. Bowen have passed over without sufficient consideration. (1) The marginal phase cannot be taken as accurately representative of the initial magma unless that contact phase be present as a glass. Crystallization itself implies differentiation. The liquid is impoverished in those components which have gone to form the solid phase, and there must be some degree of diffusion of material to the crystallizing centers. With rapid crystallization this diffusion will be minimized, but the important point in the present instance is that if crystallization has

[1] T. C. Chamberlin, *The Origin of the Earth*, 1916, p. 171.

taken place at all, then material has been selected from the magma. It is clear, therefore, that although the more rapidly cooled marginal phase will represent the general rock type of the original magma, yet it cannot be taken as giving an exact replica of that magma except in the cases where the cooling has been so rapid that all crystallization has been inhibited. (2) To assume that the marginal phase represents the primary magma cuts out the possibility that, as intruded, the mass was not homogeneous. We may indicate two general types of heterogeneity. The actual liquid which cooled at the contact may have been different from place to place, or again there may have been streaks of different composition within the mass. Either of these features would completely upset any attempt at exact calculation of the variations which have taken place in the original magma. (3) A third fallacy in this method is that it assumes, by its principle of comparing the average of the traverse with the marginal phase, that the igneous mass as we now see it was originally one magma. This assumption is certainly evident in Mr. Bain's interpretation of Knight's analyses—as already pointed out.

Leaving these general considerations and coming to the actual process of assimilation, as more fully outlined by Mr. Bain for the rocks at Sudbury, we find that it is in conflict with the principles of the crystallization of igneous rocks. Before the solvent action by the magma became at all pronounced, differentiation by gravitative settling of the first-formed crystals is considered to have taken place. Since this is a crystallization differentiation, the temperature in this part of the crust must have been falling. The crystallization in the magma was an attempt at equilibrium in this environment of falling temperature. As there would be some slight lag in the attainment of equilibrium, we must therefore assume that the walls of the reservoir would be at a somewhat lower temperature than the crystallization temperature of the minerals separated in the magma. Further crystallization would be controlled by this falling temperature gradient, so that there would be no excess energy in the system which would be available to dissolve foreign material even could we accept the extremely improbable view that sediment of the composition of quartzite, etc., could be dissolved.

In conclusion, it might be well to note the brief consideration

given by both Bain and Bowen to the possibility of there being not one but two igneous rocks involved in this outcrop. Both concentrate on the occurrence of a basic phase above the "chilled" marginal zone of the norite. Bain is evidently under the delusion that this basic phase is at the top of the norite, and Bowen pays no attention to the details of the field relations of the variations of the norite. Arguing on the false basis that the marginal material represents the original magma, they hold that there must be an acidic portion complementary to this more basic part. As already noted, all that the marginal phase indicates is that the rock, as intruded, belonged to either the gabbro or the diorite family. Even were there any truth in the arguments put forward, however, one would once more have to leave the speculative side of the problem to recognize an important fact of field evidence, viz., that, generally, the basic phase is overlaid by more acid material—a gabbro rock with quartz-feldspar mesostasis.

EVIDENCE OF ASSIMILATION AND ASSIMILATION PROCESSES

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ABSTRACT

This paper is a reply to the criticisms directed against a paper entitled "Amount of Assimilation by the Sudbury Norite Sheet," an article really intended to outline a method of determining quantitatively the amount of assimilation, but in no way pretending to explain the process or to set forth in an elaborate manner the evidence that such a process operated. In this paper an attempt is made to meet the various arguments against assimilation, to outline the process according to which it operates, and to outline in a simpler way methods of calculating composition changes by the use of series of analyses.

FIELD DATA

The Sudbury sheet was regarded by Professor Coleman[1] as an intrusive following a plane of unconformity between the Sudbury series and the Trout Lake conglomerate (Animikie). At that time the Gowganda formation (Middle Huronion) was correlated with the Lower Huronian and the Mississagi quartzite (Lower Huronian) with the Wanapitei quartzite (Sudbury series). The Norite, in most places, seems to follow the plane of unconformity across the upturned edges of the Sudbury series. In Scadding township the Bruce series (Lower Huronian) alone is said to be 7,400 feet thick[2] and is overlaid by the Gowganda formation (Middle Huronian) 3,500 feet thick. In Capreol township the Trout Lake conglomerate (Animikie), 500 feet thick, is the oldest bed present. This relationship indicates an absence of over 10,000 feet of sediments which lie between the plane of unconformity and the Trout Lake conglomerate, and therefore should be found above the norite, whereas they are absent.

Knight[3] has attempted to explain the structure of the Sudbury basin by faulting. The sediments within the canoe are regarded as

[1] A. P. Coleman, *Report Ont. Bur. Mines*, Vol. XIV, Pt. III (1905), p. 10.

[2] T. T. Quirke, *Summ. Report Can. Geol. Sur.* 1921, Pt. D, p. 38.

[3] C. W. Knight, *Report of Royal Ont. Nickel Com.*, 1917, p. 122.

having been lowered into the pre-Huronian basement and the norite as a mass injected along the same fault planes. Fault planes in general have two characteristics:

1. Normal fault planes outcrop in a straight line or smooth curve.

2. Fault planes may inclose a block, but those bounding a block of elliptical cross-section are extremely rare types.

The fact that the outer margin of the norite is very irregular and is roughly elliptical, with the longer diameter $2\frac{1}{2}$ times the shorter one, calls for some explanation other than faulting to account for the structure. It is possible that the absence of the sediments may be explained in part by an unconformity below the Trout Lake and above the Gowganda, but even this fails to offer an adequate explanation.

The mysterious absence of the sediments is merely one problem of the region. The Sudbury injective shows remarkable differentiation by gravitational settling of the mafic and calcic minerals and later crystallization of the salic residue as a micropegmatitic phase at the top of the sheet. The lower margin is distinctly fine-grained and characterized by zoned feldspars, produced by rapid crystallization or chilling at the time of injection of the magna. It seems hardly possible that chilling could have occurred at any later time, because the liquid would have warmed the walls and permitted slower crystallization with formation of a rock of texture similar to that farther removed from the cooling surface. The cooled margin then ought to be an approximate[1] sample of the original solution. The extent to which secondary processes have modified the composition may be evaluated by petrographic study; this seems to show that the changes due to processes operating after the consolidation of the magma are so slight as to be almost negligible except in instances of specimens taken from within a few hundred feet of intrusive masses of granite. Such occurrences are not known within several miles of MacLennan township, and there is no reason to suspect their presence in this region within 3,000 feet of the surface. The average

[1] As pointed out by Mr. Phemister, crystallization does imply differentiation, but if it proceeds so fast that the silicate fraction of the liquid residue fails to separate more than the distance represented by crystal growth, it is not possible that the process could affect the composition of a sample taken from an area ten feet square.

composition of all the differentiation products of the magma, taking volume into consideration, ought to be the same as that of the original solution or to appear slightly deficient in the constituents of the early minerals of the chilled border rock and have an excess of the complementary components. Instead it is deficient in the complementary constituents and differs to such a degree that not even the errors in analytical methods can explain the discrepancy. Solution in the liquid magma of rocks containing SiO_2, Al_2O_3, Na_2O and K_2O (the complementary constituents) in ratios never found in igneous types, and quite characteristic of graywacke beds, is a possible explanation of both problems.[1]

Assimilation.—The word assimilation, as used in this paper and in the preceding article by the author, means the reaction between a solid and liquid whereby the solid phase becomes fluid by passing into solution in the liquid phase, and that the entire reacting solution remains liquid long enough to allow distribution of the dissolved particles to such an extent that the form of the xenolith is destroyed. This is a fuller enunciation of the author's former statement of the problem.[2]

Field evidence of assimilation, as defined above, cannot be found in xenoliths no matter how abundant they may be, nor need we expect unusual minerals unless the magma solution becomes saturated with components to form those minerals or the magma is too small to dissolve and distribute the inclusions. Only one piece of evidence can be used to controvert the theory, and that is continuation above the sheet of the stratigraphic succession at the horizon at which it was discontinued below the injected mass. Throughout the Sudbury region a gap, represented by the absence of several thousand feet of sediments, occurs in the position occupied by the sheet. The average composition of the missing beds has not been determined, but the range includes limestones, quartzites, arkose, conglomerate of granite pebbles, graywacke, argillaceous graywacke, and iron formation. The SiO_2 content of such a series ought to be about 75 per cent and the Al_2O_3 about 5 per cent (based upon the average composition of sedimentary rocks). These figures conform

[1] G. W. Bain, *Jour. Geol.*, Vol. XXXIII, pp. 509–25.

[2] *Op. cit.*, p. 509.

to the average composition of blocks which would have to be added to the magma to produce the difference between the initial and average composition of the differentiation product.

Assimilation processes.—One question raised[1] is "What evidence does Mr. Bain adduce, of rock full of xenoliths passing through less and less contaminated material into pure gabbroic rock, that he can by calculation alone reach the conclusion that the norite magma has assimilated an amount of rock equivalent to two thirds its original volume and possibly two to three times that amount?" Abundant xenoliths, or unusual rocks, are not evidence for assimilation, nor does their absence indicate that assimilation has not occurred. Small dikes and sheets usually contain many xenoliths and unusual minerals, but intrusives equivalent in size to, or larger than, the Sudbury sheet rarely have inclusions except as indistinct ghosts along their upper margin; the roots of mountain ranges have gone into granite batholiths without leaving a trace in the form of inclusions or unusual minerals. The folded masses seem to have been stoped away and the blocks dissolved by the corrosive solution. Lack of recognition of assimilation by major intrusives is due to the completeness of the process rather than to the absence of it. Absence of rocks which, from a structural point of view, should be present constitutes the extent of field evidence of assimilation. Any solution at uniform temperature, if allowed to stand long enough, will become homogeneous throughout, especially if it is in a saturated condition. The texture of rocks in the upper part of the sheet testifies to high fluidity over a long period of time, seemingly long enough to allow equilibrium conditions to be attained throughout and for marked differences from point to point to become impossible.

Introduction of a fragment of the roof of the liquid would disturb equilibrium conditions due to increase in concentration of certain components. Those components in excess of what is required to maintain equilibrium, in accordance with the law of mass action, will be precipitated in the form of crystals. If the xenoliths have the same chemical composition as the magma, the same minerals will precipitate from the solution as would settle out if an uncontaminated magma were solidifying. Xenoliths are derived from the

[1] T. C. Phemister, *Jour. Geol.*, Vol. XXXIII, p. 819.

rocks adjacent to, and in contact with, the top of the silicate solution; series of analyses (as yet unpublished) across contact zones representing almost every possible combination of intrusive and intruded rock show that those near the contact have almost the same composition as the intrusive itself and that changes in composition extend outward with diminishing intensity. Blocks stoped into a magma solution have almost the same composition as the solution, and the same minerals will be precipitated as would crystallize out under normal conditions of lowering of solubility by cooling. Relative amounts of constituents of the solution change slightly owing to removal of material into the contact zones which are to be dissolved in the magma.

The Sudbury sheet was injected along a plane just above the pre-Huronian rocks. The oldest member left above the sheet at the present time is the Trout Lake conglomerate. Rocks which would be dissolved first include arkoses and quartzites of the Bruce series. Differentiation of the magma must have reached the micropegmatite stage before pronounced assimilation could begin, because quartzite inclusions in the smaller diabase and norite sheets of the region have extremely narrow reaction-rims, so that it is very doubtful whether enough FeO, CaO and MgO could be carried into the rock cover to change large masses of it to the composition of the norite, a change which invariably precedes solution.

Source of heat.—The portion of the sheet which was dissolving the xenoliths must have been very small, and the source of the heat necessary to liquify the solid blocks is an important factor in the problem. The basaltic parent magma must have heated the inclosing rocks to the magma temperature, or a higher one than that of the salic differentiate, before the micropegmatite stage was attained. Comparatively little heat would be required to maintain the temperature of the walls. Latent heat of solution is equal to heat of crystallization, and if one substance separates from solution, heat is liberated and will be used up in the solution of xenoliths, which have been added, to maintain a state of equilibrium. (This is analogous to purification of substances by slow crystallization). This process could continue until conduction of heat through the cover, or lack of material to change the composition of the contact rocks, halted

the activity of the magma solution. The amount of liquid is never greater than at any previous time (Fig. 1), and no tremendous amount of heat is essential to *dissolve* the sediments. The zone of active solution must constantly decrease, owing to leakage of heat

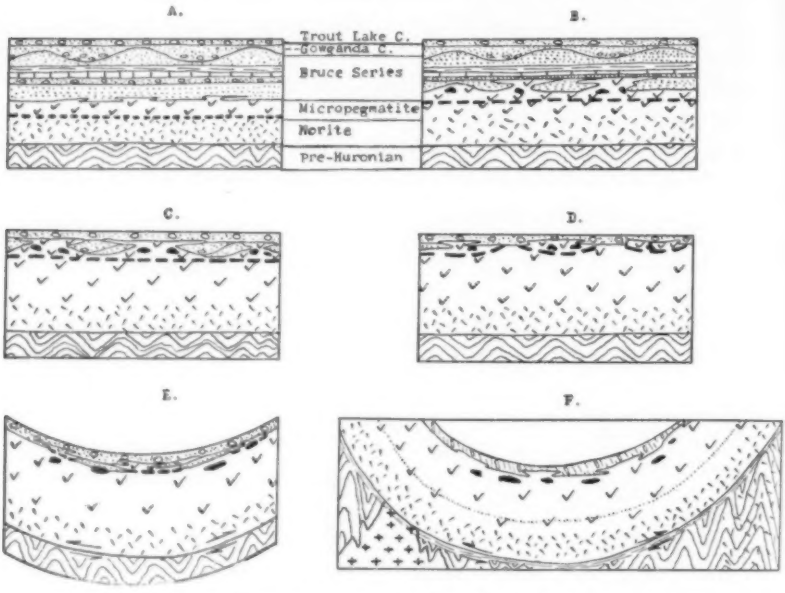

FIG. 1.—Diagram illustrating the development of the Sudbury sheet according to the assimilation hypothesis. Xenoliths are shown in heavy black. The boundary between liquid and solid phases in each stage is shown in heavy black dotted line—liquid on top and solid on the bottom. The original thickness of the sheet is shown in a light dotted line in F. In the final stages the liquid becomes concentrated in a few disconnected pockets which solidify throughout simultaneously.

and exhaustion of mineralizers, and it is in the small residue of liquid which solidifies simultaneously throughout that undissolved xenoliths may be found.

Xenoliths.—"Igneous" rocks which have an unusual mineral composition characteristically have the unusual minerals in local bunches. The structure is almost invariably that of highly "soaked" solid rocks rather than of types crystallized from a homogeneous

liquid. The Peekskill norite contains many unusual minerals such as corundum, spinel, magnetite, cordierite, and others typical of the contact zones of the region. These are syntectic products formed by reaction of a liquid and a solid; the solid was never simultaneously liquid throughout, and ghosts of the xenoliths remain outlined by patches of abnormal minerals which have held together. The author has never had an opportunity to study the Arnage norite and is

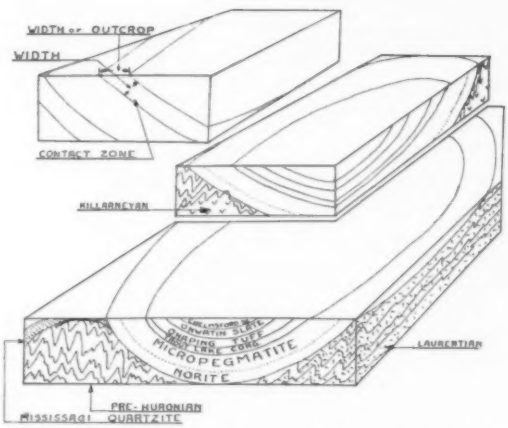

FIG. 2.—Sketch (not drawn to scale) showing the general relations of the Sudbury norite sheet to the other rocks of the region. The relation of width to width of outcrop is shown on a larger scale in the inset drawing in the upper left-hand corner.

therefore unable to express an opinion as to whether or not the unusual minerals have the same origin as in the Peekskill instance, but the similarity is very striking.

Width of contact zones.—The Trout Lake conglomerate is about 500 feet thick and, although highly metamorphosed adjacent to the underlying micropegmatite, is little changed at the top. According to Phemister, the outcrop of the contact zone around the norite is 0.25 miles wide[1], but the zone itself, in the conglomerate at least, cannot be greater than the thickness of the bed, which is 500 feet or less. (Fig. 2). The amount of material removed from the magma

[1] Phemister, *op. cit.*, p. 822.

into contact zones cannot be great; in fact, as pointed out later, it is negligible in amount.

Primary magma sample.—The presence of secondary SiO_2 in the rocks of the lower chilled margin has also been emphasized by Phe-

TABLE I

	Average Composition Basic Differentiate	Composition Corrected to 100 Per Cent (less H_2O, CO_2)	Width of Outcrop (feet)	Relative Mass (1)
SiO_2	56.10	57.38	2350	1348.8 x 10^2
Al_2O_3	19.23	19.63		461.0
Fe_2O_3	2.70	2.76		64.8
FeO	5.95	6.07		142.7
CaO	5.51	5.67		133.1
MgO	2.96	3.02		71.0
Na_2O	3.61	3.68		86.5
K_2O	1.76	1.79		42.1
H_2O	2.26	.....		.....
CO_2	0.20	.....		.....
Total	100.23	100.00		2350.0 x 10^2

TABLE II

	Composition of Chilled Margin	Composition Corrected to 100 Per Cent (Less H_2O, CO_2)	Width of Outcrop (feet)	Relative Mass (2)
SiO_2	56.21	57.52	2350	1352.0 x 10^2
Al_2O_3	22.85	23.40		550.1
Fe_2O_3	1.25	1.28		30.1
FeO	4.80	4.91		115.2
CaO	4.22	4.32		101.2
MgO	1.24	1.27		29.9
Na_2O	3.96	3.53		83.0
K_2O	3.45	3.77		88.6
H_2O	2.56	.....		.....
CO_2	.....	.....		.....
Total	100.27	100.00		2350.0 x 10^2

mister as a source of error in the calculations.[1] Silica was not used except as a dilution component, so that addition of 1 to 2 per cent would not affect the calculations to any marked degree. Lowering the SiO_2 of the chilled margin increases the amount to be added to

[1] Phemister, *op. cit.*, p. 821.

the original magma to balance the "accounts." This error tends to minimize the amount of assimilation rather than to increase it.

Basic differentiate.—The average composition of the basic differentiate can be determined by calculation and is given in Table I.

The mass of the original magma which would have occupied the same volume before differentiation is given in Table II.

TABLE III

	Average Composition Micropegmatite	Composition Corrected to 100 Per Cent (Less H_2O, CO_2)	Composition Edge	Percentage Increase in Acid End
SiO_2	67.60	68.66	57.52	11.14
Al_2O_3	13.39	13.60	23.40	−9.80
Fe_2O_3	3.67	3.73	1.28	2.45
FeO	4.13	4.19	4.91	−0.72
CaO	1.89	1.92	4.32	−2.40
MgO	1.07	1.09	1.27	−0.18
Na_2O	3.46	3.51	3.53	−0.02
K_2O	3.25	3.30	3.77	− .47
H_2O	1.53	.....	.....	.....
CO_2	0.18	.....	.....	.....
Total	100.17	100.00	100.00	00.00

TABLE IV

	I	II	III
SiO	3.20×10^2	11.14	28.5
Al_2O_3	89.00	−9.80	− 908.0
Fe_2O_3	−34.70	2.45	−1416.0
FeO	−27.50	0.72	−3820.0
CaO	−31.90	−2.40	1330.0
MgO	−41.10	−0.18	2283.0
Na_2O	− 3.50	−0.02	17500.0
K_2O	46.50	−0.47	9890.0

The salic differentiate.—The addition or removal of material from the average magma to form the micropegmatite should be the inverse of that to give the mafic end, if the difference is due to simple differentiation. Table IV, column I gives the mass of material of the original magma discarded by the basic phase (mass 2 − mass 1), and column II, the percentage of increase in components in the salic end. Column III is obtained by dividing I by II; positive values indicate

width of micropegmatite, and negative, width of basic phase in excess of 2350 feet (the actual thickness), demanded by a theory of simple differentiation.

DISCREPANCIES IN OPPOSING THEORIES

Double injection.—The sudden break in the curve representing the analyses published by Mr. Knight[1] is considered by Mr. Phemister[2] to indicate the intrusion of two separate sheets of magma. The fact that the entire basic phase (Table IV, col. I) does not even approach the amount expected from the composition of the margin shows that this part of the sheet does not form an intrusive unit separate from an upper salic portion. If the suggestion were at all tenable, the most mafic portion should be not at the top, but overlaid by a narrow salic portion. The only salic portion is the micropegmatite of rather uniform composition and regarded by Phemister as a single separate intrusive. If the salic portion is the product of a single intrusion, which it seems to be, it must be a unit along with the mafic part, and the entire mass referred to as the Sudbury sheet must be the product of a single intrusion of magma.

Simple differentiation.—On the basis of simple differentiation the width of outcrop of the salic differentiate, as shown in Table IV, must range from −3,820 feet to 17,500 feet, both of which are impossible values, and this process is therefore inadequate to account for the discrepancies.

Inflow of salic magma.—Bowen[3] suggests that the magma may have differentiated, and that flowage of the liquid salic phase into the central part of the structural basin might accentuate the importance of the salic fraction. The negative widths of outcrop (amounts by which the mafic zone is too narrow to account for differences on this basis) (Table IV) indicate that both phases of the magma have an excess of Al_2O_3, Fe_2O_3, and FeO, and that silica, lime, magnesia, and alkalies must be added to use up this residue. Alumina, alkalies, and high silica are the associates in rocks typified by micropegmatite and granite; yet in this case these constituents must become separat-

[1] C. W. Knight, *Econ. Geol.*, Vol. XVIII, p. 593.

[2] *Op. cit.*, p. 822.

[3] N. L. Bowen, *Jour. Geol.*, Vol. XXXIII, p. 828.

ed to give the desired result if we accept Bowen's hypothesis. The lower Al_2O_3 content of both magma phases is clear evidence that no amount of inflow of micropegmatite could establish a balance. Also petrographic evidence (not presented) shows complete lack of convection currents which could sweep away crystals as they settled to form the basic part.

Also if solid rocks overlying a liquid layer were folded into a canoe, some evidence of thickening ought to appear on the ends or exposed part of the synclinal as well as in the completely concealed trough.

Assimilation.—All hypotheses suggested to account for the abnormal composition of the sheet as a whole fall short when subjected to the test of the quantitative method, and it seems necessary, temporarily at least, to believe that assimilation has taken place.

POSSIBLE ERRORS IN CALCULATIONS AND THEIR MAGNITUDE

Three errors are possible in making the estimate. (1) The chilled margin may not represent the composition of the magma.[1] (2) An appreciable amount of material may have escaped upward.[2] (3) The quality of the samples and analyses may be doubtful.[3]

Error in sample of original magma.—The chilled margin may differ from the original magma owing to enrichment in certain oxides by introduction of material after consolidation, which has been considered, or to differentiation by diffusion of certain components towards the walls, or to liquid immiscibility previous to cooling. Diffusion enriches the cooler portion of the magma in alkalies at the expense of the Al_2O_3,[4] and, since these show no abnormality, the process cannot be considered to have affected materially the chilled edge as a sample of the original magma. Solidification of a liquid to give a fine texture and zoned feldspars must have been rapid, in fact almost contemporaneous with injection, and differentiation by liquid immiscibility (if such a process exists) could not have altered the composition of the magma appreciably.

[1] G. W. Bain, *op. cit.*, p. 511.

[2] *Ibid.*, p. 512.

[3] C. W. Knight, *op. cit.*, pp. 592–94.

[4] G. W. Bain, *Amer. Jour. Sci.*, 5th ser., Vol. XI, pp. 74–88.

Magma discharge in vapors.—Metamorphism is mainly along the contact of the Trout Lake conglomerate and the micropegmatite. Changes are due chiefly to recrystallization rather than to addition of outside material. Escape of a component from 5,000 feet of the magma solution, to be concentrated in a bed 500 feet thick, would mean tenfold enrichment in that component. The magma *appears* to have lost 9.43 per cent Al_2O_3; addition of 94.3 per cent Al_2O_3 to the conglomerate would mean that it ought to be composed of 48.5 per cent Al_2O_3, slightly diluted by small amounts of lime, exclusive of alumina primary to the sediment. No part contains 48.5 per cent Al_2O_3, let alone that amount of added alumina. It is almost impossible to escape the conclusion that the components discharged from the magma could not even begin to explain the composition changes in it. It still seems that, after volume has been taken into consideration, the amount subtracted by escaping mineralizers can be neglected in calculating changes in constituents, and these can be considered as due to addition of foreign material.

Errors in sampling and analysis.—Mr. Knight's method of sampling[1] is much more accurate than that adopted by most rock collectors. Errors due to analytical methods cannot be avoided altogether, but their magnitude should be kept in mind; it is hardly probable that inaccuracy could exceed 0.5 per cent for any component, an amount too small to affect the results.

THE PRINCIPLE OF DILUTION

Suppose that 20 volumes of *B* are added to a solution containing 30 volumes of *A* and 70 volumes of *B*. The final liquid will contain 120 volumes, of which 25 per cent will be *A* and 75 per cent *B*. Five volumes of *A* appear to have been removed and 5 of *B* added; but *A* has remained constant and 20 of *B* have been added. This appears to be the case of the Sudbury magma, except that in it eight components must be taken into account in determining a balance. Twenty volumes of *B* is the least which could be added to give a liquid containing 25 per cent *A* and 75 per cent *B*. Addition of 10 volumes of *A* would require 50 volumes of *B* instead of 30. The same would be true in the case of the Sudbury magma unless the rocks

[1] C. W. Knight, *op. cit.*, pp. 592–94.

added were completely lacking in one component. For Knight's section, Al_2O_3 has been added in least proportion, and the lowest alumina rock of the region contains 5.82 per cent; even the component added in least amount must have been added in large quantities.

Effect of xenoliths upon magma composition.—Attention has been called to the lack of abundant xenoliths.[1] Material removed by absorption in xenoliths[2] would be returned on their assimilation, and the final solution would be diluted by the original constituents of the inclusions rather than depleted in material added to them.

Use of magnesia and alumina in calculations.—The suggestion that FeO and Fe_2O_3 should be used instead of MgO and Al_2O_3,[3] is based upon the assumption that the discrepancies are due to interchange of components between the walls and the magma. Magnesia and alumina were used in making the calculations because they had been added in the lowest ratio in accordance with the principle of dilution. If some other component had had a lower ratio, it would have been necessary to use it. In any event FeO, which readily oxidizes to Fe_2O_3, even in granitic magmas,[4] is an extremely uncertain and dangerous oxide upon which to base any conclusions.

Refractibility—heat—solubility.—Mr. Phemister refers to the refractibility of siliceous material to assimilation by a basic magma.[5] The earlier paper[6] by the author does not suggest that assimilation was due to "fusion" by the mafic portion of the Sudbury sheet; it has always been his opinion that the micropegmatite was the solvent. In the former paper attention was centered upon the amount of assimilation in order to make that point stand out. A great supply of heat is unnecessary. It is merely necessary that the basin be large enough to hold the solvent so that it may dissolve xenoliths at the top and precipitate the excess components as mineral grains which will settle to the bottom. Melting has no part in assimilation; solution and precipitation are the operative processes.

[1] T. C. Phemister, *op. cit.*, p. 820.

[2] *Ibid.*, p. 823.

[3] *Ibid.*

[4] G. W. Bain, "Resorption," *Trans. Can. Inst. Min. & Met.*, Vol. XXIX.

[5] T. C. Phemister, *op. cit.*, p. 824.

[6] G. W. Bain, *op. cit.*

Batholithic assimilation.—The micropegmatite of the Palisades diabase breached the upper chilled edge at very few places so as to begin to dissolve the Newark sediments. The solvent micropegmatite had too small a volume to perform any large part of the task imposed upon it. Resorption of a chilled edge is essential before assimilation can commence. But the Killarney granite batholith of Ontario has removed its chilled edge, together with the Keewatin volcanics and Sudbury schists and graywackes, to the base of the Huronian. In places even the Mississagi quartzite is gone and the granite intrudes the Lorrain quartzite. Other instances of great bodies of rock removed by large intrusives might be cited, but this one ought to recall cases where enormous masses are inexplicably absent along intrusive contacts.

REVIEWS

Croonian Lecture—The Evolution and Origin of the Amphibia. By D. M. S. WATSON. London: Phil. Trans. Roy. Soc., Series B, Vol. CCXIV (1926). Pp. 189–257, figs.39.

The evolution of land forms from water-living types constitutes one of the most fascinating chapters in vertebrate evolution, but a chapter of which our knowledge has been exceedingly scanty. Many workers have of recent years made clear the structure of Permian land types and have pointed out features suggestive of an ancestry from the "fringe-finned" crossopterygian fishes. It has, however, remained for Watson to demonstrate clearly the anatomy of the earlier Pennsylvanian and Mississippian amphibians which he ranges in the group Embolomeri, and to show that they seemingly constitute the "missing link" between land and water forms. They are amphibians, but amphibians so primitive in structure that there are almost no clear-cut points of distinction between them and their crossopterygian ancestors.

A. S. R.

Text-Book of Palaeontology. By KARL A. VON ZITTEL. Vol. III. *Mammalia.* Revised by MAX SCHLOSSER. Translated under the direction of CHARLES R. EASTMAN. Translation revised, in the Additions, by SIR ARTHUR SMITH WOODWARD. London: Macmillan Co., Ltd., 1920. Pp. viii+316, figs. 374.

The translation into English of Zittel's useful textbook was begun many years ago; the volumes dealing with the invertebrates and the lower vertebrates soon appeared, and the former has passed through two editions. The final volume, dealing with the mammals, had been put in type at the time of the death of the editor, Dr. Eastman, in 1918, and now appears at last through the efforts of Sir A. Smith Woodward.

Since this translation was made from the third German edition, which has been superseded by Schlosser and Broili's later revision, the German version should be consulted for many minor additions to our knowledge in recent years. However, the more important recent discoveries, and especially the bibliographical references to them, have been added by Smith

Woodward, and the volume as revised is indispensable to those whose work relates in any way to fossil vertebrates.

A. S. R.

Nashörner der Hipparion Fauna Nord-Chinas. By TORSTEN RINGSTROM. Pekin: Palaeontologia Sinica, Series C, Vol. I, Fasc. 4 (1924). Pp. 156, figs. 92, pls. 12.

This work deals with a splendid series of rhinoceros skulls from China. The largest portion pertain to members of the short-legged Teleocerine group, for which the genus *Chilotherium* is established. An ancestor of the gigantic Pleistocene *Elasmotherium* is recognized in the fragmentary remains of *Sinotherium*. A *Dicerorhinus* and a questionable *Diceratherium* complete the fauna. Some general problems of the phylogeny of the rhinoceros group are discussed, the conclusions reached agreeing well with those of Osborn.

A. S. R.

On the Head of the Macropetalichthyids with Certain Remarks on the Heads of Other Arthrodires. By ERIC A:SON STENSIO. Chicago: Field Museum of Natural History, *Publication 232*, Geological Series, Vol. IV, No. 4, pp. 87–197, figs. 26, pls. 13.

Of all vertebrates, the systematic position of no group has been more hotly disputed than that of the Paleozoic armored fish-like Arthrodires. Of the Arthrodires, the most poorly known have been the Macropetalichthyids. *Macropetalichthys* was previously known only from the surface of the skull roof. Through the fortunate discovery in the Field Museum of an exceptional specimen, and the clever development of this find, Stensio has cleared up many problems connected with this group. Not only has he been able to demonstrate, for the first time, the structure of the brain case of an arthrodire, but also to reconstruct the cranial nerves and blood vessels and the outline of the brain. His evidence tends to show that the Arthrodires belong neither with the primitive ostracoderms on the one hand, nor the advanced lung-fish or actinopterygians on the other, but represent an aberrant side branch of the primitive shark-like fishes.

A. S. R.

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THE KATMAI MAGMATIC PROVINCE

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TABLE OF CONTENTS

PAGE

INTRODUCTION 675
ANALYSES 675
CHARACTER OF THE IGNEOUS MATERIAL IN RELATION TO ITS MODE OF OCCURRENCE 679
VOLCANIC HISTORY 685
PETROGRAPHY 689
EFFECTS OF VOLATILE CONSTITUENTS IN MAGMAS 696
OSCILLATORY ZONING OF FELDSPARS 700
COMPARISON OF VARIATION DIAGRAMS 704
ANALYSES OF OTHER ALASKAN ROCKS 705
VARIATION DIAGRAMS OF OTHER PROVINCES 709
DIFFERENTIATION 713
VARIATIONS DUE TO OTHER PROCESSES THAN CRYSTALLIZATION . . . 715
CONTACT PHENOMENA IN THE PYRENEES 718
MINERAL DEPOSITION BY VOLCANIC EMANATIONS AT VESUVIUS . . . 721
SUBLIMATES AT VULCANO AND ELSEWHERE 723
THE HYBRID ROCKS OF SKYE 724
THE HALIBURTON-BANCROFT AREA 726
THE WEST POINT, NEW YORK, AREA 730
THE SUDBURY TYPE 732

PAGE

The Heat Supply in Assimilation 738
Processes at Novarupta 740
Differential Transfer by Gases within the Magma Body . . . 743
Perret's Observations on Gas Discharge at Vesuvius 744
Lack of Differentiation in Many Field Occurrences 745
Differentiation of the Palisade Diabase 746
The Relation of Olivine to Micropegmatite 748
The Origin of Graphic Intergrowths 750
Nature of the Residual Liquor Left by Crystallization . . . 755
The Albite-Anorthite-Diopside Diagram 760
Further Discussion of the Katmai Diagram 768
Summary 771

INTRODUCTION

In the course of two seasons of field work in the Katmai region, in 1919 and 1923, a considerable collection was made of the various igneous rocks occurring there. The principal object in visiting the region was a study of the phenomena of the great eruption of 1912, and it was not possible, in the limited time available, to make a thorough investigation of former igneous activity. Nevertheless, much information was obtained, and the collections made are believed to be fairly representative.

Published analyses of igneous rocks from this portion of the Alaska peninsula are very few, and it has seemed desirable to supplement this scanty information by making a sufficient number of analyses from the new collections to show the range of composition and the relationships of the rocks of the region. As the work progressed, certain features which came to light seemed to be of significance in petrogenic theory. In order to make it reasonably certain that these relations were not the result of chance, but actually represented some governing principle, the number of analyses was extended beyond what was at first contemplated. Seventeen analyses of the older rocks of the district and one of the pumice of the last eruption have been made. In addition, several volcanic rocks from adjacent regions have been analyzed for comparison. These analyses, a petrographic description of the rocks, and an account of field relations are given in the first part of the present paper. In the second part the results of analyses of Katmai rocks and the form of the variation diagram are taken up. This leads to a consideration of processes of differentiation, and to a discussion of present-day views on causes of differentiation.

ANALYSES

The analytical procedure was that which has become well standardized in rock analysis, as embodied in the publications of Hillebrand and Washington, and requires little description. Such necessary precautions as two evaporations for the recovery of SiO_2 and two precipitations of CaO, MgO, and Fe_2O_3-Al_2O_3 were observed throughout. As regards Fe_2O_3-Al_2O_3, in fact, three precipitations

TABLE I

ANALYSES OF IGNEOUS ROCKS OF THE KATMAI PROVINCE.* FENNER, ANALYST

	284	102	299	600	257	526	249	592	286	583	575	274	568	147	253	588	104	175
SiO_2	54.10	54.29	55.44	56.12	57.85	57.76	59.28	59.11	58.66	62.97	63.82	63.72	64.12	65.51	65.59	66.81	71.22	76.53
Al_2O_3	17.59	17.08	17.67	17.67	16.47	16.06	16.73	16.71	16.20	15.67	16.04	15.87	15.69	15.79†	15.32	14.66	13.82	12.31
Fe_2O_3	3.07	3.62	3.07	6.37	2.09	4.30	2.13	1.01	3.07	2.27	2.34	2.26	3.80	1.71	1.33	2.00	.79	.46
FeO	4.94	5.23	4.74	1.63	6.51	4.51	4.59	4.92	2.74	3.64	3.41	3.57	1.94	3.50	4.09	2.71	1.66	.96
MgO	5.15	4.46	4.22	3.72	3.07	2.82	4.14	3.71	3.79	2.75	2.52	2.49	2.55	2.15	1.35	1.90	.65	.00
CaO	8.70	8.94	8.31	7.10	7.12	6.91	7.37	6.36	6.22	5.64	5.31	5.33	5.53	4.88	4.09	4.48	2.49	1.01
Na_2O	3.35	3.16	3.15	3.71	3.90	3.51	3.17	3.65	3.44	3.62	3.83	3.69	3.67	4.03	4.59	3.85	4.24	4.15
K_2O	.95	.46	.55	1.10	1.00	.68	1.33	1.12	1.29	1.55	1.78	1.74	1.86	1.64	1.67	1.95	2.54	3.05
H_2O+	.56	.90	1.39	.59	.39	.72	.21	1.63	2.42	.40	.23	.18	.05	} .01	.48	.11	1.64	.87
H_2O-	.13	.30	.11	.15	.11	.76	.10	.09	.81	.19	.03	.06	.02		.04	.06	.01	.25
TiO_2	.89	.92	.63	.91	1.08	1.07	.70	.77	.54	.67	.68	.67	.67	.56	.85	.51	.37	.17
MnO	.12	.18	.12	.14	.12	.14	.11	.10	.08	.11	.11	.12	.10	.07	.13	.07	.05	.04
BaO	.03	.03	.02	.02	.03	.02	.07	.02	.03	.02	.03	.02	.03	n.d.	.06	.06	.06	.07
P_2O_5	.40	.09	.20	.40	.23	.60	.15	.36	.35	.25	.25	.22	.29	n.d.	.43	.29	.11	.05
Cl	.06	.04	n.d.	.08	.06	.05	.02	.10	.05	.05	.08	.12	.01	n.d.	.10	.07	.13	.23
SO_3	.07	.....	.10	.10	.....	.09	.06	.09	.09	.09	.10	.17	.10	n.d.	.08	.12	.05	.....
S	.....	.38	.....	.....	.09	.....	.....	.....	.....	.....	.....	.....	.....	n.d.	.....	.....	.....	.01
CO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	.15	.37	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	100.11	100.08	99.72	99.81	100.12	100.00	100.16	99.90	100.15	99.89	100.56	100.23	100.43	99.85	100.20	99.65	99.83	100.16
Less oxygen	.....	.19	.....	.....	.04	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	.....	99.89	.....	.....	100.08	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

* Descriptions (including localities) of the rocks analyzed will be found on pages 679–85 and 689–96.

† Includes P_2O_5.

NORMS OF TABLE I

	284	102	299	600	257	526	249	592	286	583	575	274	568	147	253	588	104	175
Q	4.26	9.00	10.26	11.46	10.20	17.22	13.14	12.84	16.32	19.38	19.74	20.10	21.60	21.18	20.64	24.54	31.38	38.52
Or	6.12	2.78	3.34	6.67	6.12	3.89	7.78	6.67	7.78	9.45	10.56	10.01	11.12	9.45	10.01	11.68	15.01	18.35
Ab	33.01	27.25	27.25	31.44	33.01	29.34	27.25	31.44	28.82	30.39	31.96	31.44	31.44	34.06	38.77	33.01	35.63	34.06
An	27.52	30.86	32.25	28.36	24.46	26.41	27.24	25.58	25.02	21.96	21.41	21.68	20.57	20.29	16.12	16.68	11.12	5.00
Di	10.36	10.10	6.52	1.74	7.64	3.37	6.74	2.04	.68	6.25	2.69	2.54	3.67	3.43	1.18	2.94	.46	.....
Hy	10.40	10.84	12.46	7.80	12.37	8.38	12.85	15.30	11.02	8.44	8.44	8.90	4.70	7.93	8.08	5.91	3.22	1.19
Mt	4.41	5.34	4.41	3.02	3.02	6.26	3.02	1.39	4.41	3.25	3.25	3.25	4.41	2.55	1.86	3.02	1.16	.70
Il	1.67	1.67	1.22	1.67	2.13	2.13	1.37	1.52	1.06	1.22	1.37	1.22	1.22	1.06	1.67	.91	.91	.30
Ap	1.01	.34	1.01	1.01	0.67	1.34	.34	1.01	1.01	.67	.67	.50	.67	.....	1.01	.67	.34	.....
Hm	.....	.....	.....	4.32	.....	.....	.....	.....	.....	.....	.....	.....	.80	.....	.....	.....	.....	.....
Pyr	.....	2.28	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.51 Al_2O_3
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.35 NaCl

C.I.P.W. SYMBOLS OF TABLE I

284 ..... II.5.3′.4(5)
102 ..... II.(4)5.′4.″5
299 ..... II.4(5).′4.(4)5
600 ..... II.4(5).3′.4″
257 ..... II.4(5).3.4(5)
526 ..... II.4.3(4).(4)5
249 ..... II.4′.3(4).4
592 ..... II.4′.3.4″
286 ..... II.4.3′.″4
583 ..... II.4.3.4
575 ..... II.4.3.4
274 ..... II.4.3.4
568 ..... II.4.3.4
147 ..... II.4.3.4
253 ..... II.4.(2)3.4
588 ..... II.4.′3.4
104 ..... I.′4.2.4
175 ..... I.3(4).(1)2.′4

were usually made in order to make certain that no MgO was retained. For alkalies the Lawrence Smith method was used.

In the determinations of SO_3 and Cl, blank runs were made on the reagents. A very small correction for SO_3 was found necessary; none for Cl. In most of the analyses no attempt was made to differentiate the form of combination of sulphur, and the total is reported as SO_3 in most cases. For the very small amounts present in most of the rocks, and in view of the many ways in which it might be dissolved, combined, or adsorbed in glass or minerals, very special methods would be necessary to discriminate among the possible compounds, and even then it is doubtful whether the information would apply to its original condition in the magma. In one case (No. 102), however, the rock, though apparently perfectly fresh, contains a much larger amount of sulphur than the average. The thin section shows numerous small glints of some yellow mineral, and the powdered rock, heated in a closed tube, gives off SO_2, showing the presence of sulphides. In No. 257 also sulphides are suspected.

For CrO_3, notice was taken of the color of the solutions obtained by leaching the carbonate cakes when making the SO_3 determinations, and the absence of color (except in one doubtful case) was taken to indicate, according to accepted ideas, that no more than a trace of CrO_3 is present in any of the specimens.

In only a few samples was it considered necessary to determine CO_2. Most of the rocks are so fresh that the presence of CO_2 seems unlikely, and in addition they were examined in thin section under the microscope; where any suspicion arose, the usual qualitative test for CO_2 was made, and if any was indicated, the quantitative determination was carried out. Only in No. 286 and No. 592 was more than 0.1 per cent found. The results of these analyses are given in Table I.

In addition to the analyses of Table I, another rock was analyzed, which, by later examination of a thin section, was found to be a considerably altered rock, as is indicated also by the large amount of water. Its composition is as shown on page 679.

The thin section shows a rock which was evidently a basalt of high olivine content, but the olivines have been wholly replaced by fibrous aggregates of some mineral of a dingy yellowish-green color

No. 522: BOWLDER FROM FLOOR OF KATMAI CRATER*

SiO_2	49.01	TiO_2	.84
Al_2O_3	17.22	MnO	.18
Fe_2O_3	5.17	BaO	.04
FeO	3.68	P_2O_5	.14
MgO	6.27	Cl	.08
CaO	8.14	SO_3	.14
Na_2O	2.31	CO_2	.08
K_2O	.16		
H_2O+	1.56	Total	99.73
H_2O-	4.71		

NORM

Q	8.38
Or	1.11
Ab	19.39
An	36.14
Di	2.62
Hy	15.92
Mt	7.66
Il	1.52
Ap	.34

Symbol: II.4(5).4.5.

*Fenner, analyst.

and moderate birefringence, probably a chlorite. The feldspars, on the other hand, look perfectly fresh, and the grains of iron ore have not been oxidized; so that the alteration was probably not a weathering phenomenon, but rather one of an autogenous character induced by magmatic vapors immediately after crystallization. It is uncertain how much change of composition was effected by this process, and this analysis is left out of consideration in the subsequent discussion. At the same time it is of some interest, for the rock was evidently more basic than any of those listed in Table I.

CHARACTER OF THE IGNEOUS MATERIAL IN RELATION TO ITS MODE OF OCCURRENCE

In selecting specimens for analysis the choice was governed by the desirability of including a variety of fresh material of typical character and wide range of composition, from different localities within the district, and of various modes of occurrence. Extrusive lavas from several volcanoes, rocks from dikes, sills, old volcanic plugs, and large intrusive masses are all represented. Most specimens are from rock in place, but in a few cases specimens from bowlders[1] have been included where there could be little doubt as

[1] "Bowlder" is intended merely to imply a rock which is not in place.

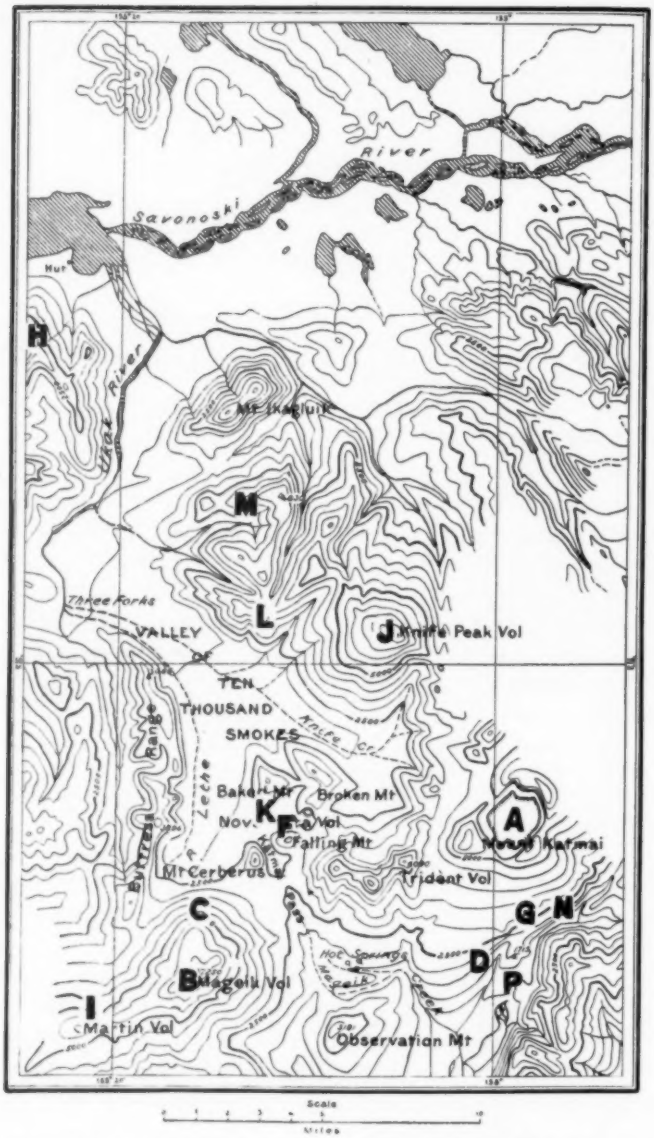

FIG. 1.—Map of the Katmai district, from drawings of the Kamishak Bay–Katmai map of the U.S. Geological Survey. Large letters indicate source of analyzed specimens. Contour interval, 500 feet.

to their derivation. Such, for instance, are some of the specimens from bowlders on the rim and floor of Katmai crater, and those from the moraine at the foot of the glacier on the northern slope of Mount Mageik (Fig. 5).

Following is a brief description of localities and modes of occurrence. Letters refer to the indicative letters placed on the map (Fig. 1).

A. No. 175: Pumice from the 1912 eruption of Mount Katmai. The composition of the ejected material varied considerably during

FIG. 2.—The crater of Mageik Volcano, looking northerly. (Photograph by C.N.F., 1923.)

the eruption, due, it is believed, to assimilation of old rocks of the mountain in the new magma. The first material ejected is a pure white pumice, almost free from phenocrysts, and is thought to represent uncontaminated magma. No. 175 is from the bottom stratum of pumice in an undisturbed deposit about 7 miles south of the crater.

No. 102 and No. 104: Lava bowlders on south rim of Katmai crater.

No. 526: Lava bowlder on floor of Katmai crater.

B. No. 583: Rock in place, bottom of Mageik crater, cliff on southerly side, near point from which Photograph No. 2 was taken.

C. No. 568 and No. 575: Lava bowlders from terminal moraine of glacier which descends the northerly slope of Mount Mageik (Fig. 5).

FIG. 3.—Cliffs of dark andesitic lava on southern slopes of Mount Katmai. Pumiceous deposits from recent eruption in foreground. (Photograph by C.N.F., 1923.)

D. No. 253: From layer of columnar black andesite (flow from Katmai), overlying stratified bowlder deposits at waterfall shown in Figure 3, on southern slope of Mount Katmai.

F. No. 147: Northerly face of Falling Mountain (Fig. 4). Falling Mountain is a somewhat isolated eminence, about 1,500 feet high, which appears to be composed wholly of a single kind of rock.

In appearance the rock suggests an extrusive lava, but the thickness of the mass and the general homogeneity of structure are extraordinary. The erosion that has left the mountain isolated indicates an ancient date.

G. No. 249: Gray porphyritic andesite from top of great masses (lava flows from Mount Katmai) near brink of Katmai Canyon, southern side of Mount Katmai, at barometric elevation of 2,250 feet.

FIG. 4.—Shattered cliff of Falling Mountain, Valley of Ten Thousand Smokes. View taken from a distance of about 1 mile. (Photograph by C.N.F., 1923.)

H. No. 299: Rock in place, summit of the mountain just south of the east end of Naknek Lake (height, about 4,700 feet). The mountain is composed of nearly horizontal Jurassic sandstones, shales, and conglomerates, with intruded dikes and sills of hornblende andesite-porphyry. At the summit is such a sill, 40–50 feet thick, from which sample was taken. Since the date of intrusion, erosion has cut to a depth of nearly 4,700 feet below the sill (in addition to removing an unknown thickness of overlying strata) and has formed flat-bottomed valleys several miles wide. A date well back in the Tertiary seems to be indicated.

I. No. 274: Lava flow, a little below the summit crater of Mount Martin, on southeasterly side.

J. No. 600: Knife Peak Volcano, about 100 feet below summit. Rock in place. Specimen collected by Charles Yori.

K. No. 588: Small block of hornblende-biotite-quartz diorite, of granitoid texture, found in the ejecta of Novarupta, on Baked Mountain. Less is known of the ultimate origin of this specimen than of any other in the collection. No outcrop of rock of this character in the district is known, but occasional blocks of similar appearance are found among the ejecta of Novarupta. It was probably brought up from the depths by the lava, though it may have been included in surface materials deposited by local glaciers overlying the site at which Novarupta broke through. In any case it probably represents an originally subjacent mass belonging within the area.

L. No. 286: Specimen from a dike about 30 feet thick, forming a noticeable "spire," jutting up from sediments on top of the ridge at the point indicated on the map. The rock is a greenish-gray feldspar-hornblende andesite-porphyry. Relations in the vicinity suggest that it is an offshoot from a large laccolith to the north.

M. No. 284: From a large mass of strikingly columnar basalt, probably an old volcanic neck or plug; the more easterly of two prominent features of this kind, rising from the surrounding sediments, on the ridge indicated.

N. No. 257: From near the bottom of the flow of columnar, black, basaltic-looking lava from Mount Katmai that overlies a surface of glacially grooved sandstone, a little above stream level, in the narrow part of the canyon of Katmai River on the northwest side.[1] The lava flow was evidently subsequent to a period of glacial action, but this may have been an early and local glaciation. The grooves exposed on the shelf overlain by the lava strike about N. 20° W. (true), or in the direction of the summit of Mount Katmai. A little to the north of here and 800–1,000 feet higher, the tops of lava cliffs at the brink of the canyon show glacial grooving which bears about N. 65° E., pointing up Katmai River toward the large, mountainous amphitheater in which the river rises.[2]

[1] Illustrated in R. F. Griggs's book, *Valley of Ten Thousand Smokes* (National Geographic Society, 1922), p. 125.

[2] Compare these relations with those in the vicinity of Mount Wrangell, as described by Schrader and Spencer (Copper River District, Alaska, *U.S. Geol. Survey*

P. No. 592: A large mass of hornblende-quartz diorite, of coarse texture, intruded among the Jurassic shales and sandstones near the lower end of the canyon of Katmai River. This mass outcrops along the northwest bank of the river for probably a quarter-mile. There are many dikes cutting the sediments in the vicinity, and the sediments themselves are slightly metamorphosed. The date of these intrusions must be rather ancient.

This list includes seven lavas which are known, or are believed, to have issued from Katmai crater at various dates: 102, 104, 175, 249, 253, 257, and 526; three lavas from Mount Mageik: 568, 575, and 583; one from Mount Martin: 274; one from Knife Peak: 600; one from an old, eroded volcanic neck: 284; one ancient dike rock: 286; one specimen from an isolated hill, apparently extrusive lava: 147; one from an ancient sill: 299; two from ancient intrusive masses: 588 and 592.

VOLCANIC HISTORY

At the time that the Upper Jurassic (Naknek) beds of the Katmai district were being deposited, volcanic activity was prevalent in a region 50–100 miles northeast (Kamishak Bay to Chisik Island), where contemporaneous strata contain a great amount of andesitic tuff and flows (?).[1] This activity, however, preceded anything represented in the present collection. Igneous activity in this vicinity seems to have begun early in the Tertiary,[2] and to have been widely distributed throughout the Alaska peninsula. Some of the material collected probably dates back to this period, as indicated by the great amount of erosion since its intrusion.

[1901], p. 57). They state: "The great sheet of andesite to the north of the Kotsina drainage lies above the mass of the Pleistocene, but gravels are found resting upon it locally and glacial scoring is also observed."

[1] G. C. Martin and F. J. Katz, "A Geologic Reconnaissance of the Iliamna Region, Alaska," *U.S. Geol. Survey Bulletin 485* (1912), p. 69.

[2] W. W. Atwood, "Geology and Mineral Resources of Parts of the Alaska Peninsula," *U.S. Geol. Survey Bulletin 467* (1911), pp. 48–49, 80–82.

In 1919, during a short landing which we made at Amalik Bay, a few miles northeast of Katmai Bay, the Tertiary (Eocene, according to Atwood, p. 49) strata in the cliffs on shore were seen to contain intercalated volcanic material, apparently contemporaneous flows, and the sediments carried pebbles of igneous rocks.

Atwood states:

> Toward the close of Eocene time an orographic movement disturbed Alaska peninsula and defined the present chain of the Aleutian Range. . . . . While erosion was in progress on the land, Miocene sediments were being deposited about the shores, so that during the period of erosion the mountain area was reduced to a land of much less relief than the present, and perhaps to a peneplain. At the close of Miocene time a renewal of mountain growth brought about a rejuvenation of the streams and opened a new cycle of erosion, which continued during the Pliocene epoch.[1]

From the Tertiary onward, volcanic activity was probably nearly, or quite continuous,[2] but the area has become restricted in recent times. The volcanoes now active are distributed along a narrow belt, and from Mount Martin northeastward through the active or recently active cones of Mount Mageik, Mount Trident, Mount Katmai, Mount Kukak, Fourpeaked Mountain, and Mount Douglas,[3] a distance of about 75 miles, the arrangement is almost linear. Knife Peak is offset, but its displacement is slight. On the other hand, older intrusives are found over a wide area on both sides of the active chain. The alinement of the recent volcanoes indicates a profound fracture in the lithosphere, and it is probably significant that this persistently active break is nearly parallel to the adjacent abrupt coast of Shelikof Strait. One is disposed to ascribe to these two features related tectonic significance.

The mountain chain along which the volcanoes are situated has in places the deceptive appearance of being wholly a mass of volcanic rocks. There are strong reasons for believing, however, that it consists essentially of sedimentary strata overlain by lava flows which buried the sedimentary topography. From the Valley of Ten Thousand Smokes and from Katmai Pass one sees on Mount Mageik no indication of other rocks than lava flows (Fig. 5), but on the western, southwestern, and southern sides the mountainous country that forms the outjutting ridges of the Mageik-Martin mass is seen to be sedimentary, and the strata attain a height of 4,000 feet on the western side of Mageik.

[1] W. W. Atwood, *op. cit.*, p. 95. [2] *Ibid.*, pp. 71–73.

[3] In regard to the volcanic nature of Mount Douglas, doubt was felt until recently. Mr. R. H. Sargent, topographer of the U.S. Geological Survey, has informed me that in 1923 he distinctly saw smoke issue on several occasions.

Similarly, the western side of Mount Katmai, from the head of the Valley of Ten Thousand Smokes to an elevation of 5,000 feet or more, is composed wholly of horizontal strata (Fig. 6), with peaks

FIG. 5.—Mageik Volcano, seen from the north. The active crater is between the two left-hand peaks. Glaciers cover most of the surface on upper part of mountain. (Photograph by C.N.F., 1923.)

FIG. 6.—Peaks and ridges of Jurassic strata on western and northwestern sides of Mount Katmai. The limits of the great crater pit left by the 1912 eruption are indicated by the arrows. View looking easterly from near Broken Mountain. (Photograph by C.N.F., 1923.)

and ridges of different topographic form from the rounded, lava-covered slopes of the same mountain on the opposite, or Katmai Valley, side.[1] To the northwest and northeast of Mount Katmai, the ruggedly mountainous topography is formed of sedimentary strata, in most places horizontal, which emerge from beneath the lava flows around the crater and continue off into unexplored territory. To the southwest of the Martin-Mageik mountainous complex the Kejulik Mountains emerge in a similar manner and trend southwestward in direct continuation of the Douglas-Martin line in the direction of the recently extinct volcano Peulik and the old craters of Chiginagak and Aniakchak. The Kejuliks appear to consist essentially of horizontal or gently inclined strata, with volcanic material among the higher peaks and ridges.[2] They rise precipitously from wide valleys.

In all parts of this volcanic range that I have been able to observe, or regarding which I have obtained information (which means a stretch from several miles northeast of Mount Katmai to well toward Becharof Lake), there are masses of sedimentary strata, capped in many places by lavas from volcanoes which are active or have become extinct at a not very ancient date. A horizontal or gently inclined attitude of the strata is prevalent, and there is no structural feature of the sediments which seems to explain the existence of this mountain range, nor in the main physiographic features of the region is there much suggestion of a pattern derived from the establishment of consequent drainage upon an uplifted peninsular mass. The situation of the line of volcanoes upon the crest of the mountain ridge seems more than fortuitous, however, and it is natural to seek as an explanation of the preservation of the

[1] Griggs's suggestion (*The Valley of Ten Thousand Smokes*, p. 127) that upper Katmai Valley may once have drained across the site of Katmai Volcano into Knife Creek Valley and been cut off by the rising lava pile is not borne out by our later knowledge, showing the presence of a mountainous wall of sedimentary strata here.

[2] This conclusion is based both upon my own observations of their character in the vicinity of Kejulik Pass, where they were crossed in 1923, and upon the statement of W. R. Smith and A. A. Baker, in *U.S. Geol. Survey Bulletin 755-D*, p. 192, who say: "The Kejulik Mountains have a very rugged appearance, showing numerous jagged peaks of igneous rock and lava-capped ridges. No distinct craters can be observed from the valley, but the extent of the lavas that can be seen on many of the ridges suggests that lava must have been poured out from several openings."

strata the protection once offered by cappings of lava, even where none is now present. Present knowledge is hardly sufficient to warrant more than a suggestion of this kind, but if it can be established by later work it will be significant in regard to the stage of volcanic activity reached. The present active centers are not sufficient to preserve more than isolated areas, and the existence of the intervening uncapped portions of the range points to greater activity in the geologically recent past. We would deduce, then, that the volcanism along this range, numerous as are the active craters, is on the decline. This is in agreement with the belief that since the Tertiary there has been a general lessening of activity in the Alaska peninsula.

Evidence is not at hand to indicate whether, during the igneous history, the composition of the rocks has followed trends of increasing and decreasing basicity, such as seems to have been manifested in some areas, but it is fairly certain that there has been no persistent trend in one direction. The rock in this collection which would be inferred to be the most ancient, No. 299, is also one of the most basic, but No. 102, from the rim of Katmai crater, and probably rather recent, is still more basic. No. 600, from the top of Knife Peak, is also basic. No. 147 and No. 588, which are inferred to be rather ancient, are more siliceous than most, but the most siliceous extrusion, No. 175, is only a few years old.

An arithmetical average of the analyses does not of itself give information regarding the average or bulk composition of the rocks in the field. For the purposes mentioned earlier, knowledge of composition over a wide range was desirable, rather than analyses in proportion to quantitative volumes of lava. In the field the impression given is of great quantities of medium to somewhat basic andesite, of composition between those of No. 249 and No. 253.

PETROGRAPHY

None of the rocks shows a composition at all unusual, and all fall within subrangs represented by many analyzed specimens in *Washington's Tables*. The mineral make-up, likewise, does not present anything different from that given in innumerable petrographic descriptions. It seems sufficient to describe a few typical specimens in some detail, and to mention some general characteristics.

In the effusive rocks the range is from an olivine basalt through hypersthene andesites and hypersthene-augite andesites and dacites to the very siliceous soda rhyolite of the last eruption. In the hypabyssal or abyssal rocks we have hornblende andesite-porphyries, hornblende-quartz diorite, and hornblende-biotite-quartz diorite.

No. 284 is the only olivine basalt among the analyzed specimens. It has been classed with the effusives, though it probably crystallized at some depth within the throat of an old volcano. Megascopically it is a dark gray, fine-grained rock, of typically basaltic aspect.[1] The thin section shows scattering phenocrysts of labradorite, olivine, and augite, large and small, in a finely granular groundmass of probably the same minerals plus magnetite. Small patches of brown glass are present. No trace of weathering is visible. Flow structure is not apparent. Many of the feldspars exhibit zoning of the progressive type, i.e., changing continuously from the center to the periphery, and not oscillating from more calcic to less, and back.

No. 102: Megascopically the rock is of a dusky neutral gray,[2] and of aphanitic texture, though minute feldspars reflect points of light. The appearance is that of a basalt.

In thin section the minerals appear fresh. Scattered plagioclase and very rare pyroxene phenocrysts occur in a groundmass of somewhat pilotaxitic texture, composed of plagioclase laths, minute pyroxene grains, iron ore, and a mesostasis of glass. Scattered grains of pyrite or similar sulphide are present.

The larger feldspars are inclined to be euhedral, though some show irregular or corroded outlines. Most are zonal in the normal

[1] The question of what constitutes a basalt has been a matter of difference of opinion. Holmes (*Nomenclature of Petrology*, p. 32) would base the distinction from an andesite upon the composition of the plagioclase. Cross ("Lavas of Hawaii and Their Relations," *U.S. Geol. Survey Prof. Paper 88*, p. 56) points out that such a basis "encounters the difficulty that the more distinct feldspars are apt to be labradorite where chemical analysis shows that much sodic feldspar and some orthoclase must be in the obscure or hyaline matrix." The lack of agreement brings up the very perplexing question of what should be the basis of rock names. This will not be discussed here, except to suggest that a few names should be left without too precise connotation, for field descriptions. In ordinary usage "basalt" seems to imply a basic, rather fine-grained rock, whose dark appearance is due to a large proportion of mafic minerals. In such a rock the first-crystallized plagioclases are naturally as calcic as labradorite.

[2] According to Ridgway's color classification.

manner. Albite twinning is common, as well as Carlsbad and traces of pericline twinning. Maximum symmetrical extinction on albite twins gives 38°, indicating molecular proportions of $Ab_{32}An_{68}$, bytownite. The laths are perceptibly more sodic: Ab_{50} An_{50}, andesine-labradorite. Some tendency to a flow structure is apparent.

Andesitic lavas are the most common in the Katmai region. In many of these the pyroxenes are both monoclinic and orthorhombic. The appearance of the two, in the Katmai lavas, is so nearly identical that it was not until the optical properties of many phenocrysts had been determined that it was considered satisfactorily settled that both forms are of common occurrence.

The monoclinic variety is an augite of positive optic character and moderate axial angle. Some crystals show a faint pleochroism, with α pale yellow and γ pale green. In the orthorhombic pyroxenes there is a distinct pleochroism, with α reddish brown, β pale yellow, and γ pale green. The optic character is negative and the axial angle is large. Maximum birefringence of the orthorhombic hypersthenes is much less than that of the augites, differing nearly one order in a section .03 mm. thick.

In some of the sections a core of hypersthene is surrounded by a shell of augite, which may be a broad band, crystallographically continuous with the nucleus, or a narrow rim made up of differently oriented grains.[1] The augite phenocrysts are much more likely than the hypersthene to show euhedral outlines, but some crystals are corroded. Probably augite is somewhat more abundant than hypersthene, though the proportions vary considerably.

These features seem to be common to many sections. The hypersthene is the earlier mineral and shows a considerable degree of replacement by augite. It might be thought, by those who attribute to crystal separation the sole cause of magmatic differentiation, that when hypersthene is observed to show instability in a basic andesite the explanation is to be sought in the changes in the composition of the residual liquid brought about by crystallization, and that by the time that dacites appear no hypersthene would be left. We find,

[1] This sequence of hypersthene to augite is not unusual in hypersthene andesites. See H. Rosenbusch, *Mikroskopische Physiographie der Min. u. Gest.* (Stuttgart, 1908), Bd. II, p. 1074.

however, that many of the dacites of the Katmai series carry abundant hypersthene, and this explanation does not seem valid. It appears that hypersthenes crystallize from the magmas of basic andesites, acid andesites, and dacites, and become unstable in all. No satisfactory explanation is apparent.

Hornblende and biotite are practically absent from the effusive lavas, but in some sections occasional aggregates of replacement minerals, generally pyroxene, feldspar, and ore grains, suggest that hornblende may, at one time, have been present.[1]

A noteworthy feature of the andesites is the manner in which oscillatory zoning of the feldspars is characteristically developed. The significance of this will be discussed later.

The effusive andesites show considerable range of color: grays, browns, reddish browns, and purplish grays occurring; and they vary from dark to light. Many are somewhat porphyritic, and the phenocrysts of pyroxene, plagioclase, and ore grains tend to be aggregated in glomeroporphyritic[2] groups in a fine-grained or glassy groundmass.

No. 250 (not analyzed) is typical of very many of the andesites. It is from a dissected lava flow in the walls of a deep, narrow canyon near the southern base of Mount Katmai. The walls of the canyon are formed of irregularly interbedded purple, gray, and reddish andesites, in many places of thinly platy structure, with surfaces of the plates dipping in various directions; or they may be massive, or, locally, scoriaceous. This specimen is of a light neutral gray (Ridgway), with phenocrysts of feldspar and pyroxene in an aphanitic groundmass. In thin section phenocrysts of plagioclase(Ab_{50}

[1] For descriptions of the replacement of hornblende by aggregates of pyroxene, plagioclase, and magnetite, see A. Lacroix, *La Montagne Pelée et ses éruptions*, pp. 508 and 557; and F. L. Ransome, "Geology and Ore Deposits of Goldfield, Nevada," *U.S. Geol. Survey Prof. Paper 66* (1909), p. 50.

[2] Glomeroporphyritic is a term introduced by Judd (*Quarterly Journal of the Geological Society*, Vol. XLII [February, 1886], p. 71). It is not quite clear whether he intended it to apply only to the peculiar groups of anorthite and olivine that he described, or to aggregates of porphyritic crystals in general, as the etymology suggests. Rosenbusch seems uncertain about this (*Mikroskopische Physiographie der Min. u. Gest.* [1908], Bd. 2, 2d half, p. 1208), but Harker accepts the more inclusive significance (*Natural History of Igneous Rocks*, p. 348). With this meaning it is a very convenient term, and is so used in the present paper. Holmes (*Nomenclature of Petrology*, p. 107) restricts it to "crystals of the same mineral." This is evidently not in accord with Judd's description.

An_{50}), hypersthene, augite, and ore appear in a granular groundmass of like constitution.

The plagioclase phenocrysts may be either euhedral or corroded. Many have an oscillatory zonal development. Some are very clear; others contain swarms of small inclusions, which favor certain zones. The inclusions consist of opaque ore and of small crystals resembling pyroxene.

In No. 251 (not analyzed), a specimen from another flow in the same canyon, the thin section is notable for the oscillatory zoning of the plagioclases. In one case forty to fifty shells of alternately dark and light zones are distinguishable under crossed nicols.

For the more siliceous lavas No. 103 (not analyzed) is a good example. It is a bowlder from the south side of the rim of Katmai crater. Megascopically, it is a pale purplish gray to neutral gray rock, carrying porphyritic phenocrysts of feldspar and pyroxene in a felsitic groundmass. Microscopically, it is seen to carry large and medium pyroxenes, medium quartz, and ore grains in an obscure groundmass, probably hyalopilitic.

The large plagioclases are both euhedral and anhedral. Zonal bands show oscillatory deposition of more and less calcic material. General composition is about Ab_{40} An_{60}. The medium plagioclases are commonly euhedral; composition Ab_{60} An_{40}. The pyroxenes are predominantly hypersthene, but augite is present. The quartz is in medium bipyramids, generally of good outlines. The rock is a hypersthene dacite-porphyry.

No. 104 is a similar rock. Megascopically, the color is a pallid neutral gray; phenocrysts of feldspar and pyroxene are visible in a fine-grained groundmass. Under the microscope: phenocrysts of plagioclase (Ab_{70} An_{30}), of oscillatory zonal development; quartz, of which many crystals are rounded; hypersthene, augite, and ore; in a clear, nearly colorless, wholly glassy groundmass, whose refractive index equals 1.490–1.495.

In addition to these common types of effusive lavas just described, a slightly abnormal variety is met with rather frequently. The groundmass, which would have been glassy under normal conditions, has been transformed in large measure to minute tridymite crystals, and the pyroxenes are partly oxidized and replaced by small

hematite scales. These transformations are believed to have been due to the pneumatolytic action of vapors given off by the lava itself on cooling, but the conditions to which the peculiarities are attributable are not known. No. 568, which is an excellent example, has almost exactly the same composition as three other analyzed specimens of normal character.

A number of rocks in the collection carry considerable quartz, and are dacites. These all came from the upper part of Mount Katmai, but this does not necessarily mean that they are of more recent date than some of the flows much farther down the mountain. It seems probable that in the building of strato-volcanoes the flows of mafic lavas will tend to advance farther down the slopes because of greater fluidity after extrusion, and this is likely to be one of the factors in producing a concave profile.[1]

The new magma of the 1912 eruption offers a great contrast to most of the rocks described. It belongs to the extreme salic pole of soda rhyolites, carries very few phenocrysts, and is of nearly pure white color. This is the type as it appears in the bottom layer of pumiceous ejecta.

A few small phenocrysts of quartz and feldspar are present, but otherwise the material is pumiceous glass of an index between 1.480 and 1.485. The quartz phenocrysts are bipyramids, many of them corroded. The feldspar shows albite twinning and a faint progressive zoning. The indices are $\alpha = 1.535$, $\gamma = 1.545$. This corresponds to Ab_{85} An_{15} if only anorthite and albite molecules are present in the phenocrysts, but with the amount of potash shown by analysis a certain amount of the orthoclase molecule is likely to have entered. The feldspar crystals are probably more numerous than those of quartz. Mafic minerals are practically absent; the minute quantity

[1] C. Gillman ("An Ascent of Kilimanjaro," *Geographical Journal*, Vol. LX [1923], No. 1, p. 2.) reasons in similar fashion regarding the effect of viscosity, but draws the conclusion that the earlier lavas were poured out in a much more liquid state than the younger. This, if intended to apply generally, does not seem warranted. With liquid and viscous flows alternating throughout the volcano's history there should always be a tendency for liquid mafic flows to reach a place near the base and assume a gentle angle of repose, and the viscous felsic extrusions to pile up near the vent. Fissure outbreaks on the lower slopes are likely to be a contributing agency in the formation of a concave profile.

appearing in certain faint streaks is believed to be the result of contamination.

Calculation of the norm shows little but quartz and feldspar molecules. As crystals of these two minerals had begun to appear simultaneously, it might be supposed that the composition is very close to that of a quartz-feldspar eutectic, but note should be taken that the ratio of 38.52 per cent quartz to 57.41 per cent feldspar is quite different from the ratio which has been held by some writers to form the quartz-feldspar eutectic in graphic granites.

The composition is shown in Table I. This analysis is almost identical with that of a sample collected by G. C. Martin in 1912 and analyzed in the laboratory of the U.S. Geological Survey. The analysis is listed in *Washington's Tables* as No. 6, on page 92, and is reproduced in the accompanying table, with No. 175 repeated for comparison.

ANALYSES OF PUMICES FROM THE KATMAI ERUPTION OF 1912, ILLUSTRATIVE OF THE NEW MAGMA IN PUREST FORM

	No. 175*	Martin's Sample†
SiO_2	76.53	76.91
TiO_2	0.17	0.18
Al_2O_3	12.31	12.18
Fe_2O_3	0.46	0.48
FeO	0.96	0.92
MnO	0.04	.....
MgO	0.00	0.00
CaO	1.01	0.92
Na_2O	4.15	4.17
K_2O	3.05	3.15
H_2O+	0.87	0.66
H_2O-	0.25	0.24
CO_2	n.d.	.....
ZrO_2	0.00	.....
P_2O_5	0.05	0.00
Cl	0.23	.....
S	0.01	0.00
BaO	0.07	.....
Total	100.16	99.81

* Fenner, analyst.
† Steiger, analyst.

As representing the plutonic rocks of the analyses, brief descriptions will be given of No. 592 and No. 588.

No. 592 is a medium gray, granitoid rock, in which crystals of plagioclase and hornblende are easily visible to the naked eye. Under the microscope, large amounts of andesine-labradorite (about Ab_{50} An_{50}), and hornblende, a fair amount of quartz, and a small amount of iron ore, with a little secondary calcite are seen. Most of the hornblende and plagioclase are approximately euhedral, and the interstices are filled with anhedral crystals of the same minerals and with quartz. The hornblende is slightly pleochroic in green and yellowish-green tints. Some of it is in feathery aggregates. The plagioclase is zonal, often oscillatory. The amount of quartz is sufficient to render the term hornblende-quartz diorite applicable.

No. 588 is a light-gray, granitoid rock, with crystals of feldspar, quartz, biotite, and hornblende visible. The microscope shows a holocrystalline aggregate of the same minerals, together with iron ore and probably a little pyroxene. The biotite has the usual pleochroism in light and dark brown, and the hornblende in light green and light brown. The plagioclase has a strong oscillatory zonal development. Quartz and plagioclase are considerably cracked, perhaps as a result of immersion in the Novarupta magma, but all the minerals are fresh and show normal properties.

In addition to the minerals mentioned there is a very small quantity of some mineral which has not been identified. It forms minute prismatic crystals of light emerald green color, with beautifully reflecting faces. The properties, so far as determined, are: α' a little greater than 1.715, $\beta = 1.720$; birefringence, probably a little greater than that of quartz; pleochroism: $\alpha' =$ yellowish brown, $\gamma' =$ green; biaxial, negative; 2E, probably 100°–150°.

EFFECTS OF VOLATILE CONSTITUENTS IN MAGMAS

In the petrogenic discussion that will follow, the influence of volatiles upon the properties of magmas is of importance in a number of ways and requires some preliminary discussion.

Probably all petrologists are agreed that magmas under great load in the depths of the crust contain a large, though unknown, quantity of dissolved substances ("mineralizers") of such character that they are easily volatilized when the pressure is removed; and that these modify in a number of ways the characteristics that a so-

called "dry melt" would possess. Among the substances of this class that are generally recognized as of leading importance may be mentioned H_2O, HCl, HF, CO_2, B_2O_3, and H_2S, or the elements from which these compounds may be formed.

Under intracrustal conditions these substances are believed to form homogeneous solutions with the less volatile materials, and their condition is one of molecular dispersal. In this state critical temperatures are so modified by complicating conditions that they probably have little relation to those of the pure substances. Gaseous properties in general are so obscured that, for most purposes, they may be disregarded, and all the substances should be regarded as parts of a mutual solution of each in the others.[1]

In a solution of this kind, even if it could be sampled and investigated, there is no means known of obtaining exact information with regard to the state of molecular combination of its ingredients. From general chemical principles, however, we are justified in the belief that the crystalline compounds that form on cooling, and the gaseous compounds that escape whenever there is opportunity, do not exactly represent, and may be very far from representing, the state of combination in the solution.

In homogeneous solutions of multiple components, subject to varying pressure, temperature, and concentration, the internal equilibrium or state of quantitative combination is continually changing. The crystals deposited are an end result of a complex series of reactions. Certain molecules may be present in large amount at one stage, yet their concentration may fail to reach the saturation point at any time during cooling. As for the volatiles, obviously they escape in those combinations that can be gasified, but in the solution there is no similar restriction to the combinations that may be formed.

In spite of the difficulties in the way of specific information we may be certain that with such active substances as the volatiles in a magma ordinary chemical laws of affinity are not suspended, and

[1] Note that these statements refer only to the volatiles when in solution. At any time when the pressure is lessened they may come out of solution and resume their gaseous properties. The purpose is to emphasize the fact that when they do go into solution the gaseous character disappears.

that the process of solution is not a chemically inert process, corresponding, for instance, to that of nitrogen in water, but that these ingredients react with the non-volatiles and with each other. For example, the halides, which are probably present in all magmas, may be expected to distribute themselves, according to their chemical affinities at a given temperature, among combinations with the bases, with silicon, with boron, and perhaps with everything present.

Although little that is definite can be stated with regard to the actual form of combination between the volatiles and the non-volatiles in a magmatic solution, yet a hint of a certain tendency is given by differences in mineral make-up between deep-seated and effusive rocks. In rocks which have crystallized at depths from magmas in which the content of volatiles is presumably large, minerals deficient in silica are apt to occur, together with free silica. Such silica-deficient minerals may be definite orthosilicates, such as olivines, or they may be more complex minerals, such as amphiboles and micas. The last two resemble orthosilicates in that the ratio of bases to silica is larger than in metasilicates, and they are often regarded as partly of orthosilicate constitution, but their sesquioxide bases play a somewhat uncertain part, and HO, Cl, and F are often present.

Hornblendes and micas are generally recognized as essentially plutonic minerals; olivines, on the other hand, appear in both plutonic and surficial rocks, and even in surficial rocks their crystalization extends into a field where there is several per cent of excess silica,[1] but there are indications that under plutonic conditions the extension into the silica field is much greater.

Information on plutonic processes is contributed by the occasional outflow of such abnormal mineralogical types of magma as the quartz-bearing olivine dacites of Mount Shasta, California,[2] and of Martinique,[3] and the olivine dacite-pitchstones of Iceland.[4] They reveal plutonic processes interrupted at a certain stage by extrusion.

[1] This is explained very satisfactorily by the experimental work of Bowen and Andersen; "The Binary System, MgO–SiO_2," *American Journal of Science*, Vol. XXXVII (1914), pp. 487–500.

[2] J. P. Iddings, *Igneous Rocks* (New York, 1909), Vol. I, p. 142.

[3] A. Lacroix, *La Montagne Pelée et ses éruptions*, pp. 507, 556.

[4] L. Hawkes, "Olivine Dacites in the Tertiary Volcanic Series of Eastern Iceland," *Quarterly Journal of the Geological Society*, Vol. LXXX (1924), No. 4, pp. 549–67.

Hawkes, in discussing the analyses of olivine-bearing acid rocks, states: "It is difficult to discover any common feature of composition which might be correlated with the presence of olivine." He seeks to explain the phenomena on the supposition that iron metasilicate does not form in the $FeO–SiO_2$ system, but the stable minerals are fayalite and free silica. This may be true, but does not seem sufficient explanation. Something additional is required by the fact that in most lavas of compositions similar to those of the olivine dacites, FeO (together with CaO and MgO) does enter the metasilicate molecule and forms pyroxenes, while it is only occasionally that we find olivine in these acid rocks.

In some of these rocks it may be observed that the olivine brought from below tends to be resorbed quickly, and persists only when the extruded lava is quickly cooled. A condition necessary for its existence seems to have been lost upon extrusion.[1]

Iddings[2] has discussed the problem of the formation of all such silica-deficient minerals—micas, amphiboles, and olivines—in high-silica magmas, and favors as an explanation the hydrolytic action of water. Though some criticism might be made, from a chemical standpoint, of the terms of his discussion, and though it might be preferable to attribute the action to a certain tendency exerted by the volatiles as a whole in effecting a changed equilibrium, rather than to the specific hydrolytic action of water, a favorable attitude may be taken toward the essential correctness of his views.[3]

A deduction from these phenomena is that the common mafic minerals of siliceous plutonic rocks tend to show a deficiency of silica, while in the rocks of corresponding composition whose crystallization has taken place in less concentration of volatiles the common minerals approach more nearly the metasilicates. If the course of differentiation be controlled wholly or in large part by the removal of crystals from the melt, any factors which influence

[1] Observations of this kind, with respect to both olivine and amphibole, have been made by H. A. Brouwer, "Crystallization and Resorption in the Magma of the Volcano Ruang," *Proc. Konink. Akad. van Weten. te Amst.*, Vol. XXIII (1920), No. 4.

[2] *op. cit.*, pp. 132–42.

[3] Phenomena of similar implication are shown in occurrences of pneumatolytic minerals in the cavities of lavas, presumably deposited in high concentration of volatiles. Lacroix, Iddings, and many others have described olivine, hornblende, mica, hematite, and magnetite, associated with quartz and tridymite.

the composition of crystals formed will necessarily affect the course of differentiation. The line of descent will be given another direction, and rocks of other compositions will result. When we turn to the Katmai variation diagram (Fig. 7), however, we see little or no evidence of a tendency for the mica- and hornblende-bearing rocks to depart from the variation lines of the pyroxene-bearing rocks. This will be taken up in more detail later.

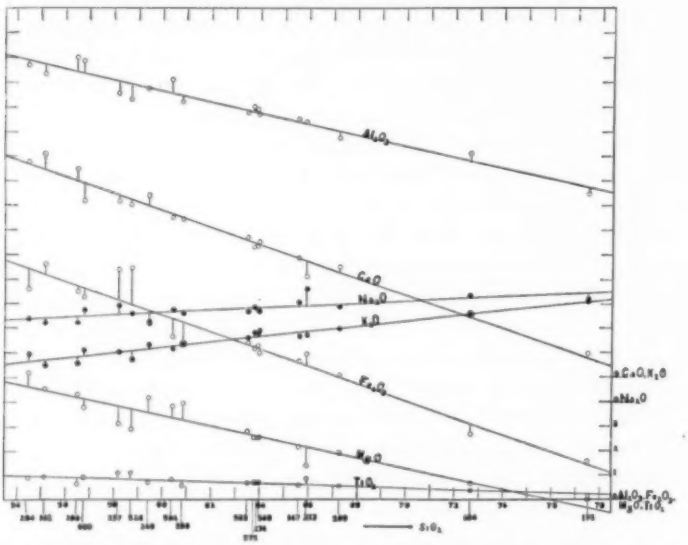

FIG. 7.—Variation diagram of igneous rocks of the Katmai province. To obviate confusion, different zero base lines for the different constituent oxides have been adopted.

OSCILLATORY ZONING OF FELDSPARS

In many of the Katmai andesites and dacites the plagioclase phenocrysts characteristically show oscillatory zoning, and this is a well-known feature of many eruptives and has been the subject of some discussion.

According to the laws of crystallization of solid solutions, the normal progress of undisturbed crystallization in albite-anorthite mixtures, either in a pure melt or in a solution containing these in-

gredients, requires that the first minute crystals should contain a greater proportion of anorthite than the melt, and subsequently the crystals and melt should vary progressively and continuously to more and more albitic composition until a minute quantity of pure albite is finally deposited. In such crystals there would be no boundaries to successive zones, but the extinction, when viewed with crossed nicols, would sweep across the crystal from center to circumference as the stage is rotated. If, instead, the zoning oscillates between more and less calcic composition, there has evidently been some disturbing influence during crystallization which has caused deviation from the normal course.

In basalts we frequently find progressive zoning, as might be expected with crystals formed under conditions of unidirectional change; it is with the intratelluric phenocrysts of andesites and dacites that oscillatory zoning is more common and more pronounced.[1] In crystals of this kind, in the Katmai specimens, there is usually an average progression in composition from the center to the periphery, but not in a uniform manner; rather, there are repeated alternations from more calcic to more sodic bands, and back to more calcic, with a trend toward a sodic composition. At times one or more bands far out toward the periphery may be seen to extinguish at the same time as the calcic nucleus; or a broad zone made up of numerous narrow bands slightly differing in composition may have almost the same extinction from inner to outer borders.

The great number of oscillations sometimes occurring is illustrated in No. 251, in which forty to fifty may be counted, although in a random thin section it is only by chance that the maximum number is exhibited. Not infrequently solution or corrosion has affected inner zones and produced irregularities. In some cases the corrosion is local; several zones are eaten out at some place, and later zones follow the irregularity, but tend to smooth it out. Similarly, crystal angles have been attacked and rounded. It is of considerable interest that in the highly siliceous dacite, No. 104, the cores of some crystals are as basic as labradorite. This seems to show that the crystals began to grow in a basaltic or similar magma.

[1] Apparently many petrologists speak of zoned crystals of feldspar only when they have in mind oscillatory zoning. More specific descriptions would be desirable.

The explanation that has been advanced for oscillatory zoning is that it is due to supersaturation.[1] It is pointed out that if the temperature drops rapidly in a solution which deposits mixed crystals, crystallization may not keep up with it, and the crystals suddenly formed at the lower temperature will not be zoned, but will have throughout the same ratio of albite to anorthite as the liquid. Plagioclases formed in artificial melts show this characteristic. When the idea is applied to magmatic bodies, however, difficulties appear. A degree of viscosity similar to that of dry melts is required, and it is very doubtful whether plutonic magmas, with their high content of volatiles, approach this condition except at the very profound depths at which the effect of pressure on viscosity becomes important. Even in surface flows, the evidence is directly against the supposition that quick cooling produces such supersaturation as the theory requires. Examination of many thin sections of extrusive basalts with this idea in mind has shown that even minute laths of feldspar, 0.03 to 0.04 mm. thick, show distinct zoning of the progressive type. Here, if anywhere, in these quickly crystallizing liquids, supersaturation might be expected to operate and produce unzoned crystals similar to those of dry melts, but it was only when increasing viscosity inhibited crystallization altogether that zonal development ceased. In andesites and dacites also the lathlike crystals of the groundmass show progressive zoning, though not so distinctly.

Moreover, to account, by the explanation given, for the sort of zoning that we find in intratelluric phenocrysts, rapid alternations of temperature are required. The sudden drop of temperature leading to supersaturation must be followed by a sudden rise, permitting normal crystallization, and this, again, by a drop. These alternations must be repeated many times.

Even granting that supersaturation might cause minor disturbances, we expect that as the liquid diminishes in amount and becomes more sodic during crystallization, the crystals should become more sodic at an accelerated rate. We find, however, in some crystals, that a central core showing progressive change of composition is followed by a wide band of slightly oscillating composition, without definite trend, or there may even be a reversal of the normal

[1] Cf. J. P. Iddings, *Igneous Rocks* (New York, 1909), Vol. I, p. 176; and A. Harker, *Natural History of Igneous Rocks* (New York, 1909), p. 233.

trend, not only suddenly, but progressively over a wide band, or sodic bands may be succeeded by a much more calcic band. It is difficult to bring these facts into harmony with the explanation that has been offered; rather, they seem to require somewhat radical changes in the composition of the surrounding liquid.

It seems more logical to look upon oscillatory zoning as a record of changes of composition of the magma brought about by external causes, and to suppose that in the intratelluric reservoir processes of differentiation have tended to change the composition in a certain direction, while at intervals accessions of original magma have carried the composition back a certain distance toward the starting-point. An alternative supposition which might be made, not very different essentially, would have the crystals settle into a more calcic portion of the magma and be carried upward again into sodic layers. A third possibility is that escape of volatiles, perhaps during an eruption of overlying magma, changes either the form of combination of constituents in the liquid or the relative solubilities to such a degree that the ratio of albite to anorthite deposited is considerably affected.

All of these processes suggest long periods of time and long suspension of crystals in the liquid. If they had settled once for all and were buried by later accumulations, growth would be stopped and successive shells of oscillating composition would not have opportunity to form.

Apart from the oscillatory zoning, the fact that phenocrysts brought to the surface with silicic magmas show change of composition through a wide range, as from labradorite to oligoclase, suggests again that the crystals remained suspended while corresponding changes in the liquid occurred.[1]

The theory of differentiation by crystallization rests upon the ability of a magma to free itself of crystals. These phenomena of the feldspars raise a question as to whether, in the primary magma reservoirs, separation by gravity is always competent against the play of other forces. Unless separation is effected, bulk composition is not changed.

[1] Rosenbusch (*Elemente der Gesteinslehre* [1901], p. 251), mentions the sporadic occurrence of calcic feldspars, even down to bytownite, in rocks of the liparite and quartz porphyry families.

COMPARISON OF VARIATION DIAGRAMS

The compositions shown in Table I have been plotted in Figure 7. In constructing this diagram the volatile ingredients have been omitted, and the remainder has been recalculated to 100 per cent. FeO has been recalculated to Fe_2O_3 and added to the Fe_2O_3 found.[1]

When the recalculated analyses are plotted it is apparent that the amount of each constituent varies in approximately linear relation of that of silica. On the assumption that the mean line for each set of constituents is a straight line throughout, the most probable position of the line has been determined by the method of least squares. The exactitude of the assumption has then been tested as follows: the eighteen analytical determinations of Al_2O_3, for example, were divided into two groups by taking the nine basic analyses in one and the nine siliceous in the other. Then a separate mean square calculation of the line for each group was made. The bipartite line thus obtained differs so little in position from the original line that the differences are hardly visible on a diagram of this scale. The same is true for CaO. The calculation has not been extended to the other constituents, but it does not seem probable that the results would be noticeably different.

The largest variations from the mean shown by any analysis appear in No. 257 and No. 526. In order to make sure that faulty analytical work was not responsible, the determination of the main constituents in No. 257 was repeated, with almost identical results. It appears, therefore, that such aberrations are actually existent; the remarkable feature is that they are so small. In the basic half of the diagram they tend to be larger than in the acid half.

The four analyses, 274, 568, 575, and 583, are striking in their correspondence with each other and with the mean lines. No. 274 is from Mount Martin, and the others are from flows from Mageik, which, judged from different megascopic characteristics of the specimens, were entirely separate.

In comparing the Katmai diagram with others it is found to be remarkable in two respects: Practically no curvature or change in

[1] It is immaterial for the purposes of the plot whether all the iron is plotted as Fe_2O_3, FeO, or Fe. The position of points will vary a little, but the characteristics of the plot will not be altered.

the slope of the mean lines for any constituent is visible throughout the range from 54.5 to 77.5 per cent SiO_2,[1] and the departures from the means are small—very exceptionally as much as 1 per cent, and seldom more than 0.5 per cent.

Such variation diagrams have been rather frequently constructed for representing the relations of a set of rocks from an area. When the analyses which form their basis in a given case are few in number, it is doubtful if this form of representation is of much value, and it may even be misleading. In order that conclusions regarding trend or lack of trend and general characteristics of the variation may be drawn, probably ten to fifteen analyses, representing considerable range, are necessary. It is only with some such number that it is possible to place proper weight upon individual aberrations in composition, or to decide whether aberration is a characteristic of the group, as is sometimes the case.

ANALYSES OF OTHER ALASKAN ROCKS

The area covered by the rocks analyzed may be seen from the map, Figure 1. It would be of interest to know how far the limits of this province might be extended before the compositions begin to depart noticeably in characteristics from those of the Katmai region, and whether the departures are gradual or sudden; but a great number of analyses would be necessary for this study. As a small contribution toward this end four new analyses of rocks from adjacent areas have been made, and are given in Table II, together with six others from *Washington's Tables*. For the specimens on which the new analyses, I–IV, are based, I have to thank the U.S. Geological Survey and the U.S. National Museum. Nos. III and IV are specimens collected by Mr. S. R. Capps, from a hill 2 miles due south of the summit of Mount Peulik,[2] and the rocks are believed by him to represent the eroded plug of a former vent. No. I is a

[1] It should be noted, however, that for MgO the mean line of compositions strikes the zero base line a little before 77.5 per cent is reached. This probably means that if all compositions were represented, the position of the line would be raised a trifle, or that its direction would change slightly for the very acid rocks. The indicated change is so small as not to be of much significance.

[2] Mount Peulik is on the south shore of Becharof Lake, 60–65 miles southwest of Mount Katmai. It is a typical volcano in form, but no historical activity is known.

specimen deposited in the National Museum, labeled "Harriman Alaska Expedition No. 131, 1899, Andesite, Loc. Kukak Bay,

TABLE II

ANALYSES OF IGNEOUS ROCKS FROM ADJACENT PARTS OF ALASKA

	I	II	III	IV	A	B	C	D	E	F
SiO_2	56.57	59.81	68.86	67.21	62.78	61.31	58.63	60.40	56.63	56.07
Al_2O_3	18.57	18.03	15.38	16.10	17.16	16.70	16.23	16.89	16.81	19.06
Fe_2O_3	4.99	3.94	1.97	3.38	1.96	1.30	1.91	1.88	3.62	5.39
FeO	1.67	.87	1.14	.63	2.31	4.08	4.20	3.72	3.44	.92
MgO	2.18	1.37	.85	1.43	2.32	3.44	4.28	3.82	4.23	2.12
CaO	7.70	6.51	3.73	4.32	4.84	6.10	6.59	7.25	7.53	7.70
Na_2O	3.44	4.46	4.10	4.06	4.11	4.05	3.51	3.80	3.08	4.52
K_2O	.96	3.12	2.40	2.29	2.15	1.58	2.09	.77	2.24	1.24
H_2O+	.80	.08	.33	.11	.88	.36	1.17	.20	.51	.99
H_2O-	1.61	.16	.13	.03	.24	.22	.15	.09	.80	.....
TiO_2	.84	.53	.34	.43	.56	.73	.74	.61	.67	1.24
MnO	.12	.18	.12	.11	.06	.14	.11	.12	.23	.23
BaO	.02	.20	.03	.07	.04	.05	.....	.06	.09	.....
P_2O_5	.44	.38	.35	.20	.15	.18	.20	.16	.16	.16
Cl	.04	.31	.10	.08	tr.	.....	.....	.....	.....	.....
SO_3	.09	.20	.22	.06	.....	.....	.....	.....	.....	.....
S	.....	.....	.....	.....	.02	.00	.02	.04	.03	.....
CO_2	n.d.	n.d.	n.d.	n.d.	.00	.00	.00	.00	.00	.....
Total	100.04	100.15	100.05	100.51	99.58	100.29	99.93	99.87	100.14	99.64

NORMS OF TABLE II

	I	II	III	IV	A	B	C	D	E	F
Q	14.94	11.10	27.66	24.42	16.74	12.66	10.32	14.46	9.12	7.80
Or	6.12	18.35	14.46	13.34	12.79	9.45	12.23	4.45	13.34	7.23
Ab	28.82	34.58	34.06	34.58	34.58	34.58	29.87	31.96	26.20	38.25
An	32.25	21.41	15.85	18.90	21.96	22.52	22.40	26.69	25.30	28.08
Di	2.59	6.48	.....	1.30	.89	5.66	5.62	6.74	8.83	6.91
Hy	4.20	.40	2.10	2.50	7.08	11.12	13.12	10.83	9.05	2.10
Mt	3.25	2.32	3.02	3.71	3.02	1.86	2.78	2.78	5.34	2.13
Il	1.52	.91	.61	.76	1.06	1.37	1.37	1.22	1.22	.....
Ap	1.01	1.01	1.01	.34	.34	.34	.34	.34	.34	.34
Hm	2.72	2.24	.....	.80	.....	.....	.....	.....	.....	5.39
Tn	.....	.....	.....	.....	.....	.....	.....	.....	.....	.39
C	.....	.....	.20	.....	.....	.....	.....	.....	.....	.....
NaCl	.....	.47	.....	.....	.....	.....	.....	.....	.....	.....
Na_2SO_4	.....	.43	.....	.....	.....	.....	.....	.....	.....	.....

LOCALITIES AND C.I.P.W. SYMBOLS OF TABLE II*

I. Kukak Bay. Fenner, analyst. II.4".(3)4.4"
II. Bogoslof Island. Fenner, analyst. II.4(5).3.".4
III. Mount Peulik. Fenner, analyst. I.4.(2)3.4
IV. Mount Peulik. Fenner, analyst. I.4.".3.4
A. Yentna River (p. 377). Stokes, analyst. (I)II.4.3.4
B. Mount Wrangell (p. 377). Hillebrand, analyst. II.4".3.4
C. Unalaska Island (p. 377). Hillebrand, analyst. II.4(5).3.4
D. Augustine Volcano (p. 403). Hillebrand, analyst. II.4.3.".(4)5
E. Unga Island (p. 489). Hillebrand, analyst. II.(4)5.3.".4
F. Bogoslof Island (p. 489). Chatard, analyst. "II.(4)5.3.4(5)

* Page numbers refer to *Washington's Tables*.

Shelikoff Straits, Alaska."[1] Its appearance is that of a surface flow. No. II, from the National Museum, is labeled "Harriman Alaska Expedition No. 146, 1899, Hornblende andesite, Loc. Bogoslof Island, Bering Sea."

The four new analyses and the six from *Washington's Tables* are represented diagrammatically in Figure 8, with the mean lines of

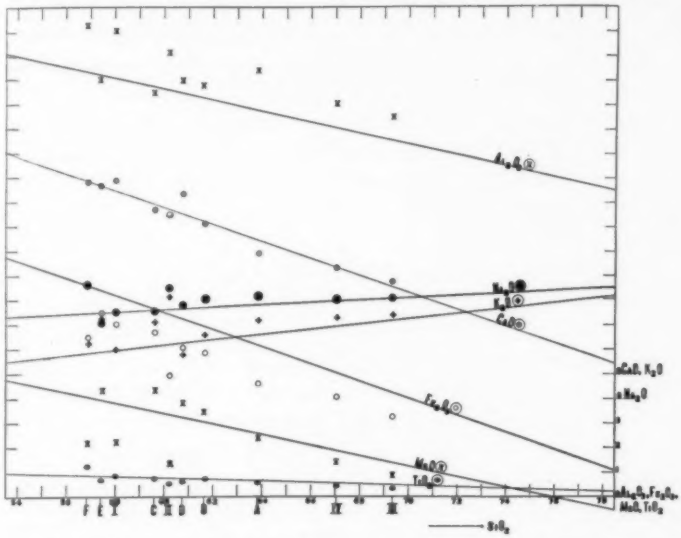

FIG. 8.—Diagram of analyses of igneous rocks from Alaskan areas adjacent to Katmai.

the Katmai diagram drawn for comparison. It is evident that the indicative points of these analyses are considerably scattered with respect to the mean lines of the Katmai diagram. Only in B (Mount Wrangell) do all the points approach closely enough to be considered a good fit. III and IV (Peulik) might be considered fair approximations, while I (Kukak) departs noticeably in MgO, Fe_2O_3, and Al_2O_3. The greatest departures are shown by II (Bogoslof).

As far as may be judged from a comparison of diagrams 7 and 8,

[1] Kukak Bay is about 25 miles east of Mount Katmai.

it seems probable that as one travels along the volcanic chain in either direction from the Katmai province the special relations that characterize the rocks of the province tend to disappear. Many more analyses would be necessary, however, before this could be considered established.

A large collection of analyses of rocks from different points along this volcanic chain would be of great interest, and should help to solve some fundamental problems. Study of maps and charts shows a remarkable characteristic of the chain, in that it pursues an uninterrupted course across the most varied terrestrial features. At its northeast end it lies among high mountains and within a truly continental region; along the Alaska peninsula the average elevation of the surface is much less; while in the Aleutians the volcanic islands form the summits of a narrow ridge rising abruptly from abyssal depths.

According to present ideas regarding isostatic compensation, the different elevations of the regions traversed are the expression of differences of density of the underlying material within the upper 60 miles or so of the lithosphere, and this chain of volcanoes extends across these regions and brings up samples of the underlying material for examination. A study of the eruptive material in its relation to these features should give interesting information.

A large series of analyses such as suggested should give information on several problems of petrogenesis. The linear form of the Katmai diagram is a notable characteristic of this area, uniting rocks of very different composition, age, and mode of occurrence. There can be little doubt that all these rocks have a common ancestry. The character is presumably the expression of two chief factors: first, the sort of material on which differentiation starts to work; and second, the processes of differentiation by which changes are brought about. With similar information obtained from several other points along the chain, and comparison of the results, we should have a much better basis than now to reach conclusions on both these points.

The close approach to rectilinear variation shown by the Katmai rocks is interesting and suggestive. The conclusion seems justified that a single process of differentiation prevailed here to such a degree

over other possible processes that only small aberrations resulted. We may not be able to explain the process fully, but it is important to have evidence that differentiation may follow such a course throughout a wide range of composition. In many diagrams there seems to be evidence of a conflict of processes which obscures interpretation. Moreover, the linear character gives a basis for at least tentative conclusions as to what sort of differentiation processes may be ruled out in this case.

VARIATION DIAGRAMS OF OTHER PROVINCES

For comparison with Katmai and in order to show some of the characteristics of variation diagrams I have recalculated to a volatile-free basis the analyses of groups of rocks from four other homogeneous provinces. These are plotted in diagrams 9, 10, 11, and 12. Two of the diagrams resemble that of Katmai; the other two are very different.

In Figure 9, forty-one analyses from the Mount Lassen region in California are shown. Twenty-seven are taken from *U.S. Geol. Survey Bulletin 591*, pp. 169 ff., and fourteen are unpublished analyses made by Dr. E. S. Shepherd, of this laboratory, which he has kindly allowed me to use. The quartz basalts of the region have not been included. They are remarkable in that magnesia and alumina depart widely (in opposite senses) from the normal values of the same constituents in the other rocks of the series, while the other constituents fall into their proper places. Harker's suggestion that these quartz basalts are hybrid rocks[1] does not seem an altogether satisfactory explanation of these anomalous aberrations of only two constituents, but to find a satisfactory explanation is difficult. Their inclusion in the diagram would confuse relations otherwise apparent, and they have been left out, but note should be taken of the fact that their existence seems to imply that at times differentiation followed an abnormal course.

With the forty-one analyses plotted, variation is almost as rectilinear throughout most of the range as it is in the Katmai diagram. Mean straight lines have been drawn, based simply on judgment as to their position. On the acid side of the diagram it is obvious that

[1] A. Harker, *The Natural History of Igneous Rocks* (New York, 1909), p. 355.

Na_2O and K_2O change direction markedly at about 70 per cent SiO_2; Fe_2O_3 and MgO seem to change slightly at about the same point; while Al_2O_3 and CaO change very little, if at all. On the basic side there are indications of breaks in some of the lines, but the number of analyses is small.[1]

Figure 10 shows twenty-two analyses of rocks of the San Franciscan volcanic field.[2] The rocks are of great variety mineralogically and chemically, including biotite rhyolite, biotite soda granite-

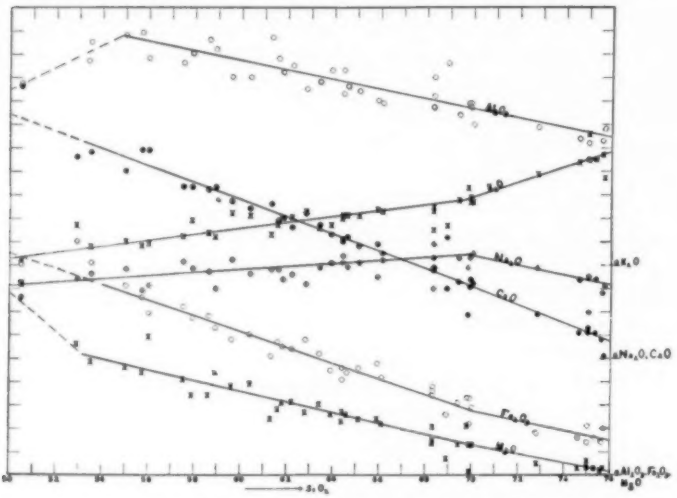

FIG. 9.—Variation diagram of the Lassen Peak region, California

porphyry, riebeckite soda rhyolite, riebeckite soda granite-porphyry, biotite dacite, biotite-hornblende dacite, hypersthene-hornblende soda dacite, pyroxene-hornblende latite, augite andesite, hornblende

[1] Day and Allen ("The Volcanic Activity and Hot Springs of Lassen Peak," *Carnegie Institution of Washington Publication 360* [1925], p. 38) give a slightly different diagram. The analyses have been divided into six groups according to SiO_2 content, and the members of each group have been averaged. The resultant mean lines are very nearly straight between 50 and 70 per cent SiO_2, but instead of breaks being shown at 70 per cent, curves are drawn. The form of the diagram is not very different from Fig. 9.

[2] H. H. Robinson, "The San Franciscan Volcanic Field, Arizona," *U.S. Geol. Survey Prof. Paper 76* (1913), p. 178.

soda andesite-basalt, augite basalt, and other varieties, as listed by the author. Notwithstanding this variety, the analyses show serial variation. The special features of this group are that for Fe_2O_3, CaO, Na_2O, and K_2O there is no definite evidence of departure from rectilinear variation throughout, while Al_2O_3 and MgO show breaks at about 66.5 per cent SiO_2.

The recent publication of the fine memoir of Mull, Loch Aline, and Oban,[1] by the Scottish Geological Survey, provides the ma-

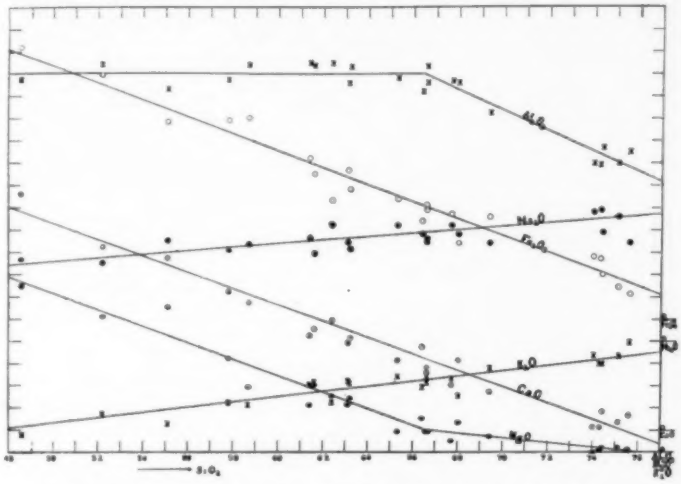

FIG. 10.—Variation diagram of San Franciscan volcanic field, Arizona

terial for Figure 11. The principal constituents of thirty-seven analyses are plotted. K_2O and TiO_2 are omitted, as their representation would confuse the diagram without contributing anything essentially different.

It appears from the geological work in Mull that the rocks belong to a definite volcanic cycle in a comparatively small area. The indicative points of the analyses are remarkably scattered, so that hardly more than an indistinct trend may be discerned. The scatter-

[1] *Tertiary and Post-Tertiary Geology of Mull, Loch Aline, and Oban* (1924), by a large group of workers. Analyses on pp. 15, 17, 19, 20, 23, 24, 27, 29.

ing is not quite so great if the rocks are divided into groups on the basis of certain characteristics; for instance, a large content of alkalies; but even then the characteristics are quite different from those of the previous diagrams. The diagram as plotted illustrates the possibilities of erratic variation from, presumably, a single parent magma.

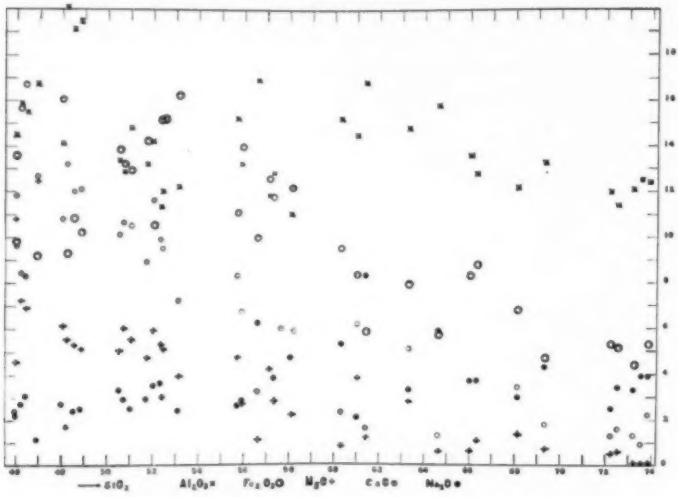

FIG. 11.—Plot of analyses of igneous rocks of Mull

Finally, in Figure 12, ten analyses of the well-known Palisade diabase sill of northern New Jersey are shown.[1] This body is several hundred feet thick and is believed to have been intruded as a single homogeneous mass. Variations, therefore, are not due to processes which occurred deep in an intracrustal reservoir, but in a region now accessible to observation.

The alkalies alone vary regularly; Al_2O_3, Fe_2O_3, MgO, and CaO show much scattering. The only principle that may be detected is the antipathetic relations of Fe_2O_3 and MgO. There is a distinct

[1] J. V. Lewis, in *Annual Report of the State Geologist of New Jersey for 1907*, p. 121. Thirteen analyses are given, but three have been omitted because of possible confusion from close proximity of points.

tendency for one of these to be low where the other is high. This sill is one of the best examples known of gravitative separation of crystals. Near the base there is a persistent stratum, about 10 feet thick, composed largely of olivine crystals. This seems to have concentrated within itself a disproportionate part of the MgO, while Fe_2O_3 is high in the more acidic upper portions of the sill.

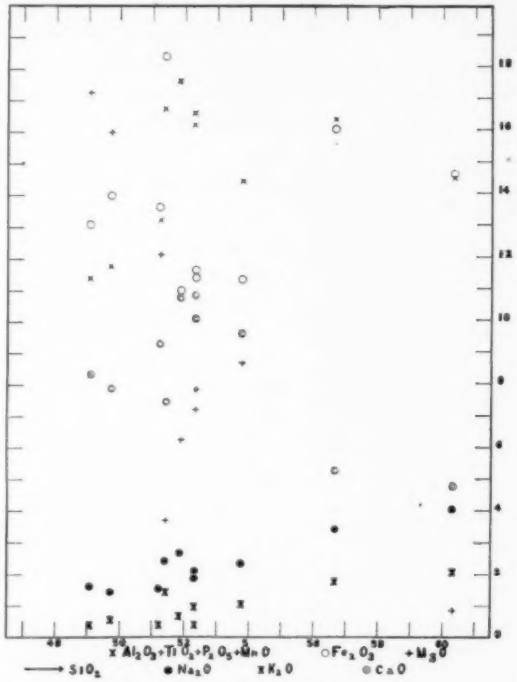

FIG. 12.—Plot of analyses of Palisade diabase

DIFFERENTIATION

The fact that a volcanic vent may, in the course of its history, eject lavas differing widely in composition is one of the most significant phenomena of volcanism. Like characteristics frequently hold true in a broader manner. Parallel features of similarity and dissimilarity unite intrusive and extrusive bodies over a wide region

and throughout a prolonged volcanic cycle. This has led to a belief that all the igneous bodies of such a province are in some way related: an idea embodied in Iddings' term, "consanguinity." It is now the general belief of petrologists that a single great body of intratelluric magma differentiates in some manner into various fractions, which may differ widely and yet preserve a family resemblance.

Some of the earlier explanations of differentiation are of hardly more than historic interest, and in any case their discussion is beyond the scope of this paper. A few years ago Dr. N. L. Bowen, of this laboratory, offered an explanation which has attracted much attention and which has been considered by many to represent a final solution.[1] Bowen's theory, of differentiation by crystallization, was based on facts which had long been noted and which had been recognized as of importance, but in his treatment the theory assumed a form which made it appear applicable in a far more general sense than had previously been recognized. Nevertheless, in the view of some petrologists the theory has not the universal applicability that Bowen has advocated, and the present writer feels a similar doubt. In some instances the operation of differentiation by crystallization seems almost demonstrable, but in others there are serious obstacles. A critical examination of some of the features of the theory seems desirable. In the following pages some of the difficulties will be discussed rather fully, not because of a belief that the theory is more open to criticism than other explanations, but, on the contrary, because its importance is so great that its possible limitations should be recognized.

Consideration will be given to two principal kinds of evidence. In the one it will be pointed out that in the examination of certain field occurrences petrologists have been led, apparently on good evidence, to the formulation of other explanations than crystal differentiation. In the other, an inquiry will be made as to the applicability of some of the evidence cited by Bowen.

[1] N. L. Bowen, especially *Journal of Geology Supplement*, Vol. XXIII (1915), pp. 1–89. Also *American Journal of Science*, Vol. XXXIX (1915), pp. 175–91; *ibid.*, Vol. XL (1915), pp. 161–85; *Journal of Geology*, Vol. XXVII (1919), pp. 393–430; *Proceedings National Academy of Sciences*, Vol. VI (1920), pp. 159–62; *Journal of Geology*, Vol. XXX (1922), pp. 177–98, 513–70.

It should be emphasized again that crystallization differentiation is here recognized as a process of great importance. If in what follows it may appear that other processes are disproportionately stressed, it is with the idea of presenting another point of view and emphasizing the belief that such processes also are capable of accomplishing important results. To the present writer field relations and theory both seem to indicate that differentiation is to be ascribed to a complexity of processes, of which one or another may prevail in a given case. Several of these have been recognized; there may be others still unknown.

Undoubtedly crystallization, with removal of crystals as formed, is capable of effecting large changes of composition in a magma. Gravity is an ever present force tending to effect the required separation. If, however, some of the results in magmas are not in accord with what is to be looked for from this process, then other processes must have intervened to prevent the abstraction of crystals from the liquid, or to accomplish results of their own independent of crystallization.

VARIATIONS DUE TO OTHER PROCESSES THAN CRYSTALLIZATION

At the outset a divergence may be noted between the views of Bowen and those of a rather large number of geologists as to the rôle to be assigned to the volatile components of magmas. Bowen has recognized their influence in modifying the form of combination of the elements of a magma, and therefore the composition of the crystals, but attributes to them very little power to accomplish the actual transfer of material. On the other hand, many geologists have described phenomena for which they have advanced explanations involving the intervention of volatiles as chief or auxiliary agents of transportation.

Assimilation of foreign material by magmas has likewise been assigned a rôle of importance in many cases, and has been held to involve not only such reciprocal reactions as Bowen has indicated in his article on the "Behavior of Inclusions in Igneous Magmas,"[1] but even a true liquefaction or solution of the contaminating substances.

[1] N. L. Bowen, *Journal of Geology*, Vol. XXX (1922), p. 513.

Examples will be cited to show the conclusions arrived at by geologists on these and related matters. The authors quoted are men whose work, one supposes, is widely known and has authoritative standing, and it might seem unnecessary to repeat their findings here. Nevertheless, something of the kind seems to be required by the fact that with some later writers, differentiation by crystallization assumes such a form as to indicate that they have overlooked, or have not sufficiently appreciated, the importance of other definitely known processes, or that they have rejected them without assignment of adequate reasons.

The development of modern views regarding transfer of material by volatiles may be considered to be a matter of the last thirty years. In this great advance economic geologists of the United States were especially active. To certain foreign geologists also great credit is due,[1] though in the earlier years certain distinguished authors—Rosenbusch, Zirkel, Brögger, Klockmann, among others—were much opposed to this conception.

In this country the principal development of the newer views was made primarily in connection with the study of ore bodies. A multitude of papers by Kemp, Lindgren, Spurr, Weed, and others, appearing in the *Transactions of the American Institute of Mining Engineers*, in *Economic Geology*, and in the publications of the U.S. Geological Survey, served greatly to modify old ideas and place the new ones on a firm footing. These articles were directed chiefly toward establishing the thesis that many deposits of metallic minerals are formed as the result of transfer of material by magmatic emanations, but attention was also paid to the great bodies of associated silicates, and a similar derivation was assigned to them.[2] Continued work and

[1] Notably J. H. L. Vogt. See, for example, the very important article "Problems n the Geology of Ore-Deposits," *Trans. Am. Inst. Mining Eng.*, Vol. XXXI (1902), pp. 125–69.

[2] Among papers of special importance may be mentioned the following: J. F. Kemp, "Ore Deposits at the Contacts of Intrusive Rocks and Limestones, and Their Significance as Regards the General Formation of Veins," *Economic Geology*, Vol. II (1907), p. 1; J. F. Kemp, "The Copper Deposits at San José, Tamaulipas, Mexico," *Trans. Am. Inst. Mining Eng.*, Vol. XXXVI (1906), pp. 178–203; W. Lindgren, "Copper Deposits of the Clifton-Morenci District, Arizona," *U.S. Geol. Survey Prof. Paper No. 43* (1905), especially pp. 160 ff.; W. Lindgren, "The Character and Genesis of Certain Contact Deposits," *Trans. Am. Inst. Mining Eng.*, Vol. XXXI (1901), pp. 226–44.

observation have placed the subject on such a firm foundation that in this country, at least, and to a very large degree elsewhere, most economic geologists accept the principles as fundamental. The present attitude, in certain of its aspects, is succinctly stated by Kemp in a recent address.

> No doubt can longer exist in the mind of any well-informed student of contact metamorphism that magmas give forth vast quantities of iron, perhaps as ferrous and ferric chlorides or fluorides, which are precipitated by bordering limestones as magnetite and sometimes specularite. That great quantities of silica and other bases than iron, such as magnesia, alumina and the alkalies may also be derived from the same source is equally shown by the associated silicates. . . . .
>
> There is good evidence for the conclusion that after the siliceous pegmatitic emissions had departed from the parent magma, iron-bearing and highly basic emissions followed. The resulting bodies of magnetite are not necessarily limited to contact zones in limestones. If not intercepted by limestones, they might travel the lit-par-lit trails a long distance from their starting-points.[1]

During this same period Michel-Lévy, Lacroix, and others in France were making notable contributions. They attacked the subject from a somewhat different angle, not paying so much attention to the phenomena of ore deposition, but studying chiefly the evidences of silicate transfer as shown by plutonic contacts and by volcanic sublimates. The writings of Lacroix are a mine of information and should be studied in detail. Only a small part of the evidence and conclusions contributed by him can be cited here.

Lacroix's "Les enclaves des roches volcaniques" appeared in 1893. A portion having application to our present discussion is that treating of the metamorphosed limestone inclusions of the Somma of Vesuvius,[2] but other observations are almost equally pertinent. Inasmuch as Lacroix's observations given here are amplified and discussed in a later publication, we shall defer their consideration for the moment, merely noting one of his important conclusions: that a great variety and large quantity of silicate minerals were deposited by volatile emanations proceeding from the volcanic magma.[3]

[1] J. F. Kemp, "The Pegmatites," *Economic Geology*, Vol. XIX (1924), pp. 715, 723.

[2] *Ibid.*, pp. 269–325.

[3] *Ibid.*, p. 313.

CONTACT PHENOMENA IN THE PYRENEES

In his studies of granitic contact phenomena in the Pyrenees, Lacroix took up another phase of the subject. Some of his more important conclusions will be summarized; the original articles should be consulted for a full presentation of the evidence.[1]

In this region the granite, normally biotitic, forms a vast massif in contact with a series of Paleozoic sediments. The granite is believed to have been emplaced by gradual impregnation, transformation, and finally incorporation of the sediments, whose place it now occupies and of which fragments, more or less modified, are found within its mass. The metamorphic phenomena are both endomorphic and exomorphic. Opportunities for study are exceptionally favorable in this mountainous region. The sediments are chiefly quartzites, limestones, and schists, and their impregnation by the granite, with the formation of broad zones of contact minerals, and their final invasion and replacement by the magma, can be followed step by step. The process takes the form both of soaking of the whole rock and the injection of distinct veins. Commonly the quartzites are feldspathized, and mica develops; slates are transformed into mica schists and even gneisses; and in the limestones a variety of lime-silicate minerals are introduced. An interesting feature in connection with the feldspathization of the schists and quartzites is that the structure of the quartz is modified and it tends to become microgranitic. This is one of the many instances to be found in the literature in which microgranitic texture is the result of replacement in solid rocks, and not due to the crystallization of a final magmatic eutectic, as is sometimes held to be the necessary interpretation.

As regards larger features, Lacroix quotes with approval a conclusion of Michel-Lévy. "The contact phenomena of eruptive rocks are the result of the transformation of a pre-existing rock . . . . under the influence of mineralizing agents, most generally accompanied by volatile or soluble elements, which, in fixing themselves in the modified rock, transform its chemical composition more or less completely." The mineralizing agents are believed by Lacroix to be directly comparable with the volatile emanations from volcanoes.

[1] A. Lacroix, "Le granite des Pyrénées et ses phénomènes de contact," *Carte Géologique de France*, Tome 10, No. 64, 1898–99, and Tome 11, No. 71, 1899–1900.

At one place a considerable deposit of magnetite exists, at the contact of granite and limestone, and sending veins into both. It is associated with iron silicates: melanite, diopside-hedenbergite, and a very ferruginous hornblende. The deposit is explained as the result of the local increase in iron of the emanations of the granite. The mineral associations recall those of many iron deposits in crystalline rocks.

At contacts with limestone the granite has undergone great endomorphic changes, with production of basic minerals. In places there are multitudes of inclusions of the limestone within the granite, showing various degrees of alteration, and transitional phases may be traced between these and small masses of basic rocks. The existence of the basic masses is held to be closely connected with the metamorphism of the limestone. "Without wishing to say that all the peridotites, hornblendites, norites, diorites of varying basicity, and amphibole granites must necessarily result from the transformation of a granitic magma by the assimilation of calcareous sedimentary beds, I have had in view the demonstration that these transformations can be produced."

A reply by Lacroix to certain criticisms which had been made with regard to his views reaches the fundamentals of theories of differentiation.

> There has been objection to the theory of endomorphism in that it ought to be demonstrated by the comparison of analyses of the different rocks whose mutual relations it explains. The chemical composition of the granite being known, and that of the sedimentary rocks which are supposed to have been digested by the granite being given, and on the other hand, the composition of the different endomorphic types resulting, it should be possible, by aid of a formula of mixture, to pass from one to the other. The exactitude of such reasoning implies two postulates; in the first place, that the composition of the actual granite represents the whole chemical composition of the magma from which it is derived, and that all the phenomena to be explained have operated in a closed vessel without any reaction of the walls on the magma; in the second place, that all the metamorphic phenomena have been effected without partial introduction or escape of material.
>
> Now we have just seen that all the facts of observation plead against these two postulates. One cannot admit that the actual composition of the granite represents exactly that of the magma from which it proceeds, nor that its emplacement has been effected in a closed vessel. . . . .

We find ourselves in the presence of an unknown which we cannot determine quantitatively and which consists in the nature and the quantity of the volatile or transportable products lost by the granitic magma in consolidating under the form of granite. We can only appreciate this unknown by the result of its action in metamorphic transformations, of which I have demonstrated at the same time the extreme variability and the remarkable complexity.

In support of this argument, a striking example of the relations of a lherzolite to its surroundings is cited from a previous bulletin:

The lherzolite, essentially magnesian and almost free of alkalies, is surrounded by a thick metamorphic zone, characterized by rocks entirely silicated, formed out of calcareous Liassic marls, and composed of biotite, dipyre, orthoclase, albite, tourmaline, etc., all alkaline or borated minerals. Is it possible to speculate on the magma from which the lherzolite comes, by considering only the actual chemical composition of this rock and sweeping to one side what its metamorphic aureole teaches us?

Although it is recognized that metamorphic effects along contact zones in the Pyrenees continued until after a part of the granite had solidified, many of the contact phenomena are believed to imply a liquid magma at high temperature, whose emplacement was effected by slow and progressive impregnation and assimilation of the sedimentary terrains whose place it occupies. Evidences of dissolution are demonstrated by the numerous endomorphic types described. "The intensity of the endomorphic phenomena shows that the crystallization of the granite had not commenced when the magma reached the limestones, and that consequently its temperature was very high." This is in contrast with the view, sometimes taken, that *lit par lit* injection, intrusion of pegmatites, and general contact-metamorphic phenomena must be the result of the final act of a crystallizing and inert magma rather than the accompaniments of a highly heated, liquid, actively invading body. At both periods and at all intermediate stages there is likely to be expulsion of mineral-bearing emanations which impregnate the wall-rocks and, arriving at cooler zones, give rise to secondary solutions.

Lacroix expresses his conception of the general nature of the processes as follows:

I have endeavored to demonstrate . . . . that the characteristics of the phenomena of exomorphic contact of this type reside essentially in the transfer of volatile or transportable materials emanating from the magma and modifying generally in a manner more or less profound the chemical and mineralogical constitution of the sediments traversed. . . . .

In the regions which are the object of this study, and in many others, the disposition of the metamorphic beds in relation to the granite, the existence in its midst of sedimentary fragments which, in spite of their transformation, have preserved the same orientation as the peripheral schists and limestones of which they are a dependence, finally the absence of important dislocations at the immediate contacts, tend to show that the granitic magma has been emplaced in a slow and progressive fashion by soaking and dissolution of the sediments for which it has substituted itself.

In proportion as the granitic magma rose in the sedimentary beds it was preceded and accompanied there by its cortège of transforming emanations, and what it had to dissolve to make place for itself was not normal sediments, but soaked rocks, transformed or in process of transformation by fixation of emanations from its own mass.

MINERAL DEPOSITION BY VOLCANIC EMANATIONS AT VESUVIUS

Another important field of study to which Lacroix has given much attention is the volcano Vesuvius, and he has written a number of papers upon its various phenomena. After observing the eruption of 1906 he prepared a memoir, of which a large part is devoted to mineral and rock transformations and which contains much information on pneumatolytic processes.[1]

Among the tuffs of the Somma, the most striking among the masses torn from the throat of the volcano are crystalline aggregates of silicates resulting from the partial or complete transformation of limestones. Drusy cavities in these are considered to have been formed, "not by the action of the magma itself, but by pneumatolytic corrosion, effected by volatile or transportable products emanating from it." The principal minerals found in these cavities of the limestones are tabulated as follows:

Minerals rich in alkalies	sanidine, leucite, nephelite, phacelite, sodalite, davyne, meionite, hauynite, hornblende, biotite
Minerals without alkalies, but with fluorine or hydroxyl	idocrase, cuspidine, fluorite, apatite, humites
Minerals without either alkalies, fluorine, or hydroxyl	wollastonite, anorthite, grossularite, pyroxenes, spinel, melanite, magnetite, calcite.

[1] A. Lacroix, "Étude minéralogique des produits silicatés de l'éruption du Vésuve (Avril, 1906)," *Nouvelles Archives Du Muséum d'Histoire Naturelle* (1907), Quatrième Série, Tome Neuvième, Premier Fascicule.

In non-drusy limestones some of the preceding minerals and also humboldtilite, lazurite, periclase, forsterite, pyrrhotite, galena, blende, molybdenite, and graphite are found.

Aggregates entirely silicated occur. One large block is described as being composed principally of grossularite with a cavity covered with biotite, on which repose magnificent crystals of idocrase and sodalite.

In addition to these silicated limestones, the leucitotephritic lavas themselves exhibit many interesting phenomena due to similar processes or to the auto-pneumatolytic action of the lava upon itself. As an example: "The veinlet of orthoclase, sodalite, etc. traversing a doleritic leucite-tephrite . . . . has recalled to me in striking fashion those veinlets of nephelite aplite, some millimeters or centimeters thick, which traverse the essexites and nephelitic gabbros of Madagascar, Brazil, etc."

In various situations minerals not listed above occur: microsommite, aegirite, sylvite, anhydrite, chloromanganokalite, and many others.

The mechanism of such transformations is discussed. Scacchi and Vom Rath had considered them to be due to actual sublimation and redeposition of the minerals, but such action is impossible for most of them, and Lacroix believes their elements to have been transported as chlorides, fluorides, and so forth, which deposited the minerals by subsequent reactions. He points to the fact that many of the newly formed minerals contain volatile substances: chlorine, fluorine, hydroxyl, and sulphuric anhydride, and that all the blocks are still impregnated with soluble chlorides and sulphates.

Attention is drawn to the parallelism between these phenomena of the Somma and of Vesuvius and those exisiting around the contacts and in the pegmatitic offshoots of igneous massifs. A comparison is suggested also between these superficial manifestations and such deep-seated processes as the formation of greisen, and impregnation with tourmaline, topaz, and axinite; and the continuity between the processes is emphasized.

Especial interest attaches to certain sanidinites. They are ordinarily composed predominantly of sanidine, nephelite, and sodalite, and often contain hornblende. "I regard them as produced in the pneumatolytic way, in the cracks of metamorphosed limestones,

and as comparable in all respects to the pegmatitic rocks of granitic magmas." Such concentrations of alkaline feldspar, together with feldspathoids and some hornblende, which, in the theory of crystallization differentiation, would probably be regarded as the product of crystallization of the mother liquor of a magma, are here found to have been produced by pneumatolytic emanations from a magma in which crystallization was negligible as a causative factor. This evidence should not be regarded as indicating that such feldspathic veins may not be formed as the result of crystallization differentiation, but they do indicate that they may be formed in an entirely different manner also.

SUBLIMATES AT VULCANO AND ELSEWHERE

At Vulcano, in the Aeolian Islands, no metamorphosed limestones brought up from the depths appear to be present, but the sublimation products of the fumaroles deposited at the surface are of interest. Bergeat[1] lists the following elements and compounds: Sulphur, seleniferous sulphur, tellurium, realgar, boric acid, sodium chloride, ammonium chloride, iron chloride, glauberite ($Na_2SO_4CaSO_4$), lithium sulphate, Glauber salt ($Na_2SO_4 10 H_2O$), alum (containing thallium, rubidium, and caesium), hieratite (potassium silicofluoride), cobalt, zinc, tin, bismuth, lead, copper, iodine, phosphorus. Bergeat calls attention to the similarity of elements present to those in the tin ore deposits of Altenberg-Zinnwald and the copper-tin ore deposits of Cornwall.

In the Valley of Ten Thousand Smokes the fumarole gases, which contain H_2S, HCl, and HF, in places leach the pumice and leave almost pure SiO_2, but usually the orifices of the fumaroles are sites of deposition of material brought from below. The throats are lined with crusts of ferric oxide, and magnetite, pyrite, galena, sphalerite, and covellite in recognizable crystals have been collected. A great number of other substances have been determined chemically by Dr. E. G. Zies, and will be reported later.

During an eruption of the volcano Donyo L'Engai in East Africa, in 1917, according to Hobley, "a vast amount of material was ejected from the mountain, and the country for many miles

[1] A. Bergeat, "Die äolischen Inseln," *Abhand. der k. bayer. Akad. der Wiss.* (1899), 2 Cl., 20 Bd., 1 Abth., p. 193.

around is covered with a pall of grey volcanic ash and soda."[1] Water holes became so fouled with soda that they were unusable. More detailed investigation of the composition of the deposited salt would have been valuable.

This deposition of alkaline salt recalls Palmieri's description of one phase of the Vesuvian eruption of 1872. His account reads: "Not only the Vesuvian cone, but the whole adjacent country, appeared white for many days, as if covered with snow, when exposed to sunlight. This was due to the sea salt contained in the ashes with which the surface was strewn."[2]

And in another place he states: "Even chloride of iron, which was so abundant in the lavas, was scarcely perceptible in the smoke, which almost exclusively deposited sea salt on the surrounding rocks; I say sea salt advisedly, and not chloride of sodium, to show that I include all that sea salt contains."[3]

THE HYBRID ROCKS OF SKYE

Among some of the leading British petrologists there has been what seems almost an excess of caution in accepting such views as those of Lacroix and others cited. This may be due to the infrequent occurrence in Great Britain of the striking phenomena that have impressed geologists in other lands, but it seems as if a judicial examination of evidence that had been submitted would carry considerable conviction; especially, that the direct evidence in connection with volcanoes would require a minimum of extrapolation in its application to plutonic rocks. However, Harker, who has been a principal opponent, occasionally comes very close to some of the views expressed above, though he considers their application limited.[4] For instance, although he has found in Skye repeated occurrences of large masses of hybrid rocks produced by assimilation, he believes that this process is active only under exceptional conditions, and that the hybrid rocks should be of recognizably abnormal

[1] C. W. Hobley, "A Volcanic Eruption in East Africa," *Journal of East Africa and Uganda Natural History Society* (1918), No. 13, p. 339.

[2] L. Palmieri, *The Eruption of Vesuvius in 1872*, translated by Robert Mallet (London, 1873), p. 97.

[3] *Ibid.*, p. 121.

[4] See, for example, various passages in "The Tertiary Igneous Rocks of Skye," *Memoirs of the Geological Survey of the United Kingdom*, 1904.

characteristics. This restriction, however, is modified later by recognition of a process termed selective diffusion, but as diffusion in the strict sense is now generally looked upon as an extremely slow process in liquids, selective removal in a volatile phase seems indicated. Harker's views may be illustrated by the following extracts:

> We have so far regarded admixture as a simple process, and tacitly assumed that a hybrid rock derived from the two normal types, A and B can be represented in respect of chemical composition, by such a formula as mA+nB, where m and n are the proportion in which the two parent rocks mingled. In fact, however, this is not the case, the process of admixture being complicated by diffusion. We have seen . . . . that the composition of the granophyre modified by grabbro débris on Marsco does not correspond with a simple formula of the kind suggested; and . . . . we have seen abundant evidence that diffusion has proceeded more or less freely, even in some cases where the sharp boundary between the two rocks involved has not been obliterated. If, as is generally supposed, the origin of diverse rock types among normal igneous rocks is in great part dependent upon diffusion, this consideration may go to modify in some degree the argument advanced above concerning the necessarily abnormal composition of hybrid rocks, but it is at most a mitigating factor.[1]

And again:

> If in the laboratory we fuse together two rocks of known composition in known proportions we can calculate the composition of the resulting product; but the conditions which make this possible . . . . are conditions not realized in nature. The processes which have operated in the cases of the Kilchrist and Marsco rocks were of a less simple kind, mere admixture being supplemented by diffusion. . . . . In other words, the series consisting of two extreme rock-types, and the various hybrid rocks which they have generated will not in general be a "linear" series as regards chemical composition.[2]

Harker, therefore, has recognized the necessity of postulating selective transfer of material in the magma. Whether the process is to be regarded as true diffusion or as transfer in a separate gaseous phase is less important than is recognition of the fact that there are such selective processes in operation. He had already shown in connection with these hybrid rocks that conditions were such that "intermixture by flowing was not possible, and . . . dense inclusions were not able to sink in a lighter medium," which indicates that crystal settling was not the cause of the selective change of composition.

[1] "Tertiary Igneous Rocks of Skye," p. 232.

[2] *Ibid.*, p. 183.

A rather incidental remark of Harker's may have considerable significance. "In those granophyres which enclose evident xenoliths, or preserve the outlines of destroyed xenoliths, the druses often seem to stand in relation to the xenoliths. . . . . The association of druses of various kinds, usually of small size, with xenoliths is a very general phenomenon, as appears clearly in the literature of the subject."[1]

Is it not possible that these bubble cavities represent gas which was distilled from the magma into the pores of the xenoliths, and was not wholly reabsorbed when the xenoliths were dissolved? Such a hypothesis of gas-filled pores seems to assist in finding an answer to the rather mysterious problem of the method by which interchange of material takes place between the interior of xenoliths and the surrounding magma. Under such circumstances transfer by bodily convection within the minute pore spaces is ruled out, and some kind of diffusion is required; but diffusion in liquids is an extremely slow process, and severe restrictions are imposed if the liquid channels are merely capillary spaces forming a few tenths of a per cent of the rock, yet selective interchange of material on a large scale is known to be effected.[2] In a gaseous medium diffusion is many times as rapid as in liquids.

THE HALIBURTON-BANCROFT AREA

Probably one of the most effective pieces of geological work ever carried out, in the conviction it has inspired as to the enormous capacities of igneous emanations to transport material, is the study made by Adams and Barlow in the Haliburton-Bancroft region in Canada.[3] The results are embodied in a memoir of the Department of Mines.[4]

[1] "Tertiary Igneous Rocks of Skye," p. 185.

[2] For a good example, carefully studied, see H. H. Read, *Geological Magazine*, Vol. LXI (October, 1924), No. 10, pp. 433–44.

[3] In 1913, in connection with the twelfth session of the International Geological Congress, an excursion was made to this region under the guidance of Professor Adams and Dr. Barlow. I had the pleasure of participating in this excursion, and was thus enabled to view the phenomena under the most favorable auspices. The prodigious scale on which the processes had operated and the clearness of the evidence were a revelation.

[4] F. D. Adams and A. E. Barlow, "Geology of the Haliburton and Bancroft Areas," *Department of Mines Memoir No. 6* (Ottawa, Canada, 1910). The section on contact phenomena of the granite-gneiss, beginning on p. 87, is of especial value.

The phenomena described by Adams and Barlow are regarded by them as analogous in many ways to those described by Lacroix for the Pyrenees. With respect to certain features there is a difference of view, but this hardly affects conclusions as to the transporting ability of igneous emanations, with which we are chiefly concerned here.

It is impossible to summarize effectively in the space allowable the great amount of valuable information, and only a few of the more striking features can be presented.

Huge granitic batholiths invaded in domelike uplifts deeply buried pre-Cambrian sediments, prevailingly limestones. Contact metamorphism was intense, and metamorphosed fragments sank deeply into the magma. Subsequent denudation has exposed the contacts and has given sections deep within the heart of the batholiths, and the metamorphosed inclusions everywhere persist. Previous to engulfment of the sediments by the granite, emanations from it had transformed the limestones into bodies of basic silicates (amphibolites) which may be seen in process of development on an impressive scale along the contacts, and when the engulfment followed, the blocks submerged were no longer limestone, but silicate aggregates, and it is almost exclusively as silicates that the inclusions are found at all depths exposed. Many of the inclusions were softened, and appear as *schlieren* in the acid granite. These phenomena, together with the structure of the granite, show that intrusive movements began when the rock was a fused magma actively invading the wall rocks, that they continued through its history, and were brought to an end only upon complete solidification.

Amphibolite inclusions, mostly of the derivation indicated, are estimated to form about 10 per cent of the whole mass; grey gneiss, much of which, at least, represents a further stage of the softening and digestion of inclusions, forms another 10 per cent; while the red granite-gneiss forms 80 per cent. In addition, great masses of silicate rocks derived from limestone are found around the margins of the batholiths.

With this short summary of the main relations, the ideas of Adams and Barlow may best be presented by quotations in their own words. First, a definition of what they imply by the term

amphibolites, frequently used by them in a rather broader sense than usual:

> The amphibolites then may be defined as dark-colored basic metamorphic rocks, which have as their chief constituents hornblende and plagioclase feldspar. The hornblende is often replaced in part by pyroxene or biotite; while quartz, calcite, iron ore, and sphene are frequently present as accessory constituents.

Other quotations follow:

> It is evident . . . . that the invading granite under deep-seated conditions has, in many places, at least along its border, changed the invaded limestones into amphibolites and pyroxene gneisses. . . . . The most striking result of this action is that the granite, while everywhere breaking through the limestones, always holds inclusions not of limestone but of amphibolite.

At a certain locality

> the amphibolite inclusions become very numerous and often present the appearance of portions of contorted beds. . . . . The field evidence is scarcely susceptible of any interpretation other than that, under the influence of the granitic intrusion, the limestone has, in the zone of most intense action, been altered into an amphibolite. . . . .
>
> The field evidence is strongly in favor of regarding this grey rock as the limestone, altered along the margin of the batholith by the immense amount of granitic material which has been intruded through it. . . . .
>
> The alteration is due not only to the proximity of the main mass of the granite, but to the immense amount of granitic material which occurs intruded through the series, sometimes in large masses, but very frequently in thin bands which have found their way in between the beds of the invaded limestone, changing it into amphibolite and presenting a typical instance of lit-par-lit injection. . . . . The granite not only penetrates this amphibolite series, but floats off masses of it. . . . . The fragments, moreover, sometimes have a somewhat flowing form, as if they had been subjected to a certain amount of movement when in a softened condition. . . . .
>
> While the detached masses of amphibolite often preserve their angular form, ... they sometimes seem to have been softened and rendered more or less plastic. . . . . In . . . . the township of Sherbourne, where there is an enormous development of the amphibolite, very dark in color, and usually nearly massive . . . . the gneiss can be seen running into these masses in arms, tearing off fragments, which, when they become separated, are often stretched out, curved, and twisted as if they had been softened and rendered plastic. These, when pulled out very thin, seem to pass into ill-defined grey streaks in the gneiss. . . . .

As a result of these movements there develops, from a mass of granite filled with amphibolite inclusions, a more or less regularly banded rock, consisting of alternate layers of reddish gneiss and dark amphibolite.

On the matter of determining to what extent the grey gneiss as a whole has resulted from solution of amphibolite in the red gneiss, we read that "it is certain that in many places these streaks of grey gneiss represent inclusions of the amphibolite impregnated with gneissic material," but "very strong evidence should be forthcoming before concluding that all the grey gneiss in the area is a product of the solution of amphibolite fragments in the red gneiss."

Large exposures of coarse anorthosite were found, which, in places, contained strings of green pyroxene, but generally was nearly white and consisted almost wholly of labradorite. Its relations made it almost impossible to consider it as other than an alteration product of the limestone. Such occurrences may have great significance in their bearing upon the problem of the formation of anorthosites.

The nature of the processes to which the transformations are due is presented in the following words:

The changes are the result of the transfusion into the limestone of certain constituents . . . . present in the granite magma. A remarkable fact in connection with the alteration is that the granite is an acid variety, containing a very small amount of biotite as its only bisilicate, and has, notwithstanding this fact, transfused into the limestone not only silica, alumina, and alkalies, which might be expected, but also large amounts of magnesia and iron. The limestone evidently fixed certain exhalations of the granite magma in relatively greater abundance than others, exerting a species of selective action. Many cases have been described in which the granite magma passed by differentiation into a gabbro, but here the granite retains its normal character up to the contact, and at the same time changes the limestone into a rock having the composition of a gabbro.

To demonstrate the character of the progressive changes, analyses were made of three specimens from a typical series of exposures. The results are summarized as follows:

The limestone can be seen, under the influence of the granite intrusion, to have changed into a typical hornblende feldspar amphibolite, passing through the intervening stage of a pyroxene scapolite-hornblende feldspar amphibolite. . . . . A comparison of the analyses shows that the granite at first transfuses into the limestone silica, alumina, oxides of iron, and magnesia, with some alkalies and a small amount of titanic acid. As the alteration progresses, all

these constituents continue to increase in amount. But in these later stages of the alteration the alumina, oxides of iron, and alkalies are added in relatively greater proportion than the other constituents, while no further addition of magnesia or lime takes place. . . . . This final product of the metamorphism of the limestone, when compared with igneous rocks, readily takes its place as an andose, a group which includes many rocks which are commonly known as diorites, gabbros, basalts, diabases, and essexites.

In these transformations of limestone to amphibolite large quantities of the original calcium carbonate must have migrated elsewhere. It is evident also that the volatiles which acted as carriers in the magmatic transfers were only in small measure locked up in the silicate rocks. These features suggest the possibility that a considerable amount of magmatic material, non-volatile as well as volatile, may have been carried to distant regions.

W. G. Foye has studied portions of the Haliburton area in an endeavor to explain the relations of the nephelite syenites to the granites.[1] He accepts unreservedly the processes that Adams and Barlow have described. From his own observations and from study of Adams and Barlow's map, he states:

A conservative estimate would show that the amphibolites formed from 30 to 40 per cent of the limestone areas and from 10 to 15 per cent of the gneissic areas.

The contacts of large oval masses of gneiss with the surrounding limestones usually are characterized by a zone of amphibolite mingled with limestone. The average zone is one-quarter to one-half a mile in width, and represents a thickness of from one to two thousand feet.

For the formation of nephelite syenites he proposes an interesting theory, in which he attributes an important rôle to pneumatolytic gases. He supposes that soda solutions were given off by the interaction of the limestone with the granite magma, and that these soda solutions enriched certain confined portions of the magma.

THE WEST POINT, NEW YORK, AREA

It is not often that geological conditions are favorable for observing the intermediate and final stages of silication of limestones in such perfection as in the examples quoted from the works of Lacroix

[1] W. G. Foye, "Nephelite Syenites of Haliburton County, Ontario," *American Journal of Science*, Vol. XL (1915), p. 413.

and of Adams and Barlow. Often the plutonic masses have invaded rocks which were already of silicate composition, and the selective transfers accomplished by emanations are not so easily susceptible of demonstration. Nevertheless, many writers have believed that even under such conditions plainly recognizable evidences may be found. It is with the recognition of such processes that Berkey and Rice have described the complicated series of crystalline rocks of the West Point quadrangle in New York.[1]

A few extracts will suffice to illustrate.

> Igneous injection is related to magmatic differentiation, to syntexis, to magmatic movement, and to igneous impregnation and contact effects. These are, as a matter of fact, only the different expressions of the whole complicated process of deep-seated rock-making during igneous invasion. . . . .
>
> Doubtless very fluid condition and high content of mineralizers or emanations, together with high temperature and great depth or pressure, are conditions favorable to such type of penetration.

Under "Contact and Metamorphic Products of Complex Origin":

> This class includes limestones that are thoroughly silicated and represent typical contact influences, and rocks that have been impregnated and injected by igneous materials. . . . . The products are chiefly gneisses of great variety in quality and composition and structure.

Under "Impregnation Gneiss":

> Typically it ought to contain grains belonging to the original rock intimately associated with grains of introduced origin connected with magmatic invasion. Although the conclusion is fully justified that such rocks occur in considerable abundance in this district, the finding of suitable illustration material is difficult, and in even the best occurrences it is doubtful whether one could with certainty distinguish between the two sets of components.

The difficulty of discriminating between differentiation proper and effects due to other causes is illustrated in the following:

> It seems to us that an additional process of very large influence is syntexis, or the absorbing of country rock by invading magmas. Blocks of country rock have been included as distinct xenoliths, and probably no competent observer would question either their abundance or their significance. It is also clear that such xenoliths may be found in practically all stages between that of almost

[1] C. P. Berkey and Marion Rice, "Geology of the West Point Quadrangle, New York," *New York State Museum Bulletin 225 and 226*, 1921. See especially the section on petrogenesis, beginning on p. 29.

complete independence and little modified condition to that of almost complete destruction. . . . . It may, indeed, be that more of what appears to be a differentiation effect is really due to incomplete syntexis, with failure to redistribute the different matters that have been incorporated, than to differentiation proper.

THE SUDBURY TYPE

We shall pass now to the consideration of a type of intrusive complex illustrated by the nickel-bearing norite-micropegmatite at Sudbury, Ontario.

This rock body appears in surface outcrop as an oval area surrounding a basin composed of conglomerates, sandstones, tuffs, and slates, the whole having extreme dimensions of 36 and 16 miles. The average width of the intrusive varies from 1.9 to 3.1 miles. From the earlier work of Coleman, Barlow, and Walker, the structure was regarded as indicating the intrusion of a great sill or laccolith between a roof of sediments and a floor of older crystallines. A sagging or collapse of the floor resulted in the basin structure. The intrusive consists of an inner zone of micropegmatite immediately surrounding the central area of sediments, and an outer zone of norite. Ore bodies of nickeliferous pyrrhotite occur near the outer contact of the norite with wall rock, which has been regarded as the floor of the sill before its collapse, and the sulphides were supposed to have settled out of the intrusive by gravity.

In earlier years this body seemed to illustrate the principles of gravitative separation in almost diagrammatic form, and it has been frequently cited as an example. With later mining developments the relations have been found much less simple than first supposed. The later evidence has been presented and discussed by C. W. Knight.[1]

Knight shows that in places around the outer margin the contact of norite and older crystallines is vertical, or even dips outward, and that a gigantic dikelike form of intrusion is probably as characteristic as the sill-like form. For several reasons Knight suggests an alternative explanation of the origin of the basin: that a great block of the earth's crust, capped with sediments, was gradually faulted down, and that the intrusive forced its way upward and around the faulted block.

[1] C. W. Knight, "Geology of Sudbury Area," in *Report of the Royal Ontario Nickel Commission* (Toronto, 1917), p. 105.

With regard to the deposition of the ores, there are differences of opinion still far from being reconciled. Coleman has always favored the idea of gravity separation of molten sulphides from the magma, with some later rearrangement by circulating waters. Knight prefers to regard them as due to heated, mineral-bearing waters emanating from a deep-seated reservoir of igneous material after the norite had solidified. Descriptions of the manner of occurrence of the ores seem to present difficulties in accepting either view without modification. It is hard to avoid the feeling that the ores are genetically related to the norite, and gravity may have played a part in their separation; at the same time it appears as if liquid or gaseous emanations from the magma had had much to do with concentrating them in their present positions.[1]

Of considerably greater interest to us at present, however, is the question of causes of differentiation or variation in the norite-micropegmatite, and here again there are found considerable differences of opinion. Harker, "from a limited personal examination of the mass," found "no indication of a regular composition gradient in either norite or granophyre, considered separately, while the transitional zone between them has all the characters of a hybrid rock."[2]

Earlier analyses appear to Knight "to demonstrate that the rock is more basic at the outer edge than at the inner edge, but they also demonstrate, at the same time, that the middle portion of the intrusive is even more acid than part of the inner edge itself." Later, seven samples were collected at the Creighton mine at distances of 140 to 3,250 feet from the outer edge. "The analyses of these samples . . . . demonstrate that practically no differentiation has taken place in the intrusive for about two-thirds of a mile from its

[1] See a recent paper by Coleman in *Geological Magazine*, Vol. LXIII (March, 1926), No. 741, p. 108, written in reply to an article on "Magmatic Ores," by J. W. Gregory, in *Transactions of the Faraday Society*, Vol. XX (1925), p. 449; also letters by J. W. Gregory and A. Harker in *Geological Magazine*, Vol. LXIII (April, 1926), No. 742, pp. 190–92. Gregory comes to the conclusion, in the article just cited, that deposits of magmatic ores in general, in the sense of direct consolidations from a molten magma, are of relatively small importance, but recognizes that the waters which have deposited primary ores are probably in most cases of magmatic origin.

[2] A. Harker, "Differentiation in Intercrustal Magma Basins," *Journal of Geology*, Vol. XXIV (1916), p. 555.

outer edge." Similarly, seven samples at the Murray mine showed no indication of differentiation for 1,900 feet to the northwest of the basic edge. With regard to the transition zone Barlow states: "There is no sharp line of demarcation between the acidic and basic portions of the nickel-bearing eruptive, but the change, though gradual, is usually sharp enough to enable a boundary to be placed between these two types with tolerable accuracy."[1]

In a later article by Knight[2] are presented the results of analysis of seventeen samples taken at nearly equal intervals across the outcrop, the width along the line chosen being 8,300 feet. The analyses fall into two groups. From the edge inward for 2,100 feet the rocks are basic, with some variation in composition, but no perceptible trend; from 2,600 to 7,100 feet, they are of medium acidity, with similar lack of trend. The higher silica group is higher in potash, but contains no more soda than the other. The evidence available from analyses seems to indicate that the norite and micropegmatite are fairly homogeneous in themselves and do not approach each other in composition except along a rather narrow zone of transition.

A number of explanations have been offered for the variations found in the Sudbury rock mass. Coleman in his earlier work suggested that the differentiation of norite from micropegmatite was effected mainly by gravitation; later he preferred another explanation,[3] based on Daly's interpretation of similar occurrences elsewhere. Coleman's modified view involves stoping and solution of blocks of the overlying conglomerates, together with impregnation and solution of the conglomerate in place. There is at Sudbury a remarkable contact effect of the micropegmatite upon the sedimentary conglomerate, such that in places the boundary vanishes and the two blend.

Harker, as we have seen, offered an explanation implying sepa-

[1] A. E. Barlow, "Report of the Nickel and Copper Deposits of Sudbury," *Geological Survey of Canada* (1904), p. 85.

[2] C. W. Knight, "The Chemical Composition of the Norite-Micropegmatite, Sudbury, Ontario, Canada," *Economic Geology* Vol. XVIII (September, 1923), p. 592.

[3] A. P. Coleman, "The Sudbury Laccolithic Sheet," *Journal of Geology*, Vol. XV (1907), No. 8, p. 759.

rate intrusion and slight intermingling of two magmas. Bain,[1] finding that the mean composition of the chilled contact rocks at the base is quite different from that of the mass as a whole, and that the variation curve of compositions cannot be explained by gravitational settling, looked for an explanation in large-scale assimilation of quartzitic sediments, of which a great thickness is missing and not otherwise accounted for. His calculations lead to an estimate of assimilated material so large as to be difficult to accept—67 per cent as a minimum, and 150 to 300 per cent as a more probable figure. Possibly an alternative assumption regarding the form of the intrusive (as indicated by Knight) would permit an estimate more in accord with what one looks upon as reasonable. Bowen[2] thinks that the relations should be explained by gravitative crystallization differentiation, together with flow of an excess of salic differentiate toward the center of the basin, induced by dynamic movements at a time when the norite had solidified and the micropegmatite was still fluid.

The Sudbury intrusion illustrates a certain remarkable association of rock types, found in many places. The typical relation shows a large mass of basic rock (gabbro, norite, or similar material) below, usually not varying greatly in composition from one part of the mass to another; then, a relatively thin transition zone of hybrid rock; and next in order, a large mass of fairly uniform granophyre, usually of decidedly red color, passing either by imperceptible stages or somewhat abruptly into a quartzose sediment, which, by contact action, has been impregnated with granitic material. In the metamorphosed sediments and in the siliceous and intermediate phases of the igneous rock micropegmatitic intergrowth is highly characteristic. In these bodies the granophyres seem to be the last to solidify and send dikes into the others. In places xenoliths of the sediments are found in the gabbro, and are then surrounded with a reaction zone of intermediate rock similar to the rock of the upper zone, or

[1] G. W. Bain, "Amount of Assimilation by the Sudbury Norite Sheet," *Journal of Geology*, Vol. XXXIII (1925), p. 509.

[2] N. L. Bowen, "The Amount of Assimilation by the Sudbury Norite Sheet," *Journal of Geology*, Vol. XXXIII (1925), p. 825.

they may be so digested as almost to have disappeared. Examples in which most of these characteristics are found are Pigeon Point, Minnesota;[1] Moyie, British Columbia;[2] Sudbury, Ontario; Gowganda, Ontario;[3] and the Bushveld, South Africa.[4]

The explanation of phenomena of this type seems to me to be looked for in large part, at least, in the processes advocated by Daly.[5] Daly's theory involves assimilation of the quartzose material by the intrusive, accompanied and followed by magmatic differentiation. To this I would suggest a modification of such sort that the last clause would read "*preceded*, accompanied, and followed by magmatic differentiation," and would intend to imply by this that before and during assimilation of the quartzose body it was soaked with volatile material emanating from the magma, and that a modification of composition of the magma and the sediment was thus effected, much of the material lost by the magma being retained by the sediment.

Daly, in the article quoted, has extended his conclusions to granites in general, and thinks "it is quite possible that most intrusive granites are either of this origin or have been more or less

[1] W. S. Bayley, "The Eruptive and Sedimentary Rocks on Pigeon Point, Minnesota," *U.S. Geol. Survey Bulletin 109*, 1893.

[2] R. A. Daly, several articles, especially "The Secondary Origin of Certain Granites," *American Journal of Science*, Vol. XX (September, 1905), p. 185.

[3] N. L. Bowen, "Diabase and Granophyre of the Gowganda Lake District, Ontario," *Journal of Geology*, Vol. XVIII (1910), p. 658.

[4] The great Bushveld complex has been described in part in a number of publications of the Geological Survey of the Union of South Africa, e.g., by A. L. Hall, in *The Geology of the Country Southwest of Lydenburg*, 1913, and *The Geology of the Haenertsburg Gold Fields*, 1914. Some of their earlier interpretations, however, have been modified by their later work. I am indebted for my information chiefly to Dr. F. E. Wright, who accompanied the Shaler Memorial expedition in 1922 and studied parts of the region in company with geologists of the Union. Granitization of the quartzites of the roof of this body has been effected on a large scale, and syntectic granitic magmas have been formed, but how much of the total mass of granophyre, felsite, and granite is to be attributed to these processes is not yet certain. In the lower (noritic) portion of the complex, sharply defined bands of pyroxenite, anorthosite, magnetite, peridotite, and chromite are prominent. Their present relations do not appear to be explainable by crystal settling, though this process may have participated. In some parts of the complex peculiar vertical pipes of dunite occur.

[5] R. A. Daly, "The Secondary Origin of Certain Granites," *American Journal of Science*, Vol. XX (1905), p. 185.

modified through assimilation." Before going to this length, however, it would be desirable to have more information. The evidence hardly seems to justify such a generalization.

The remarkable association of micropegmatitic or poikilitic intergrowths of quartz and feldspar with complexes of this type, occurring both in the granophyres and in the quartzites, has attracted attention. Coleman asks: "Can it be that micropegmatite is a structure specially belonging to rocks where basic magmas have stoped down and digested or otherwise absorbed more acid rocks?"[1] Daly, too, calls attention to it.[2] Collins[3] has described several instances of micrographic intergrowths of quartz and feldspar in inclusions of quartzite in diabase. His conclusions are of interest:

> How important these textural features may prove to be in diagnosing cases of magmatic assimilation is something that will appear as a multiplicity of examples are compared. It is probable, however, that their value will be a limited one. In each of the examples given above assimilation has been imperfect. . . . . On the other hand, a great deal of assimilation must have taken place along the contacts between the granite-gneiss batholiths and the schist-complex, yet the textural peculiarities described above are not very common. . . . . It is possible, therefore, that the textures in question are due to imperfect fluidity, and will, consequently, be found to be restricted to cases of imperfect assimilation.

This view seems a very reasonable one, and in accord with the evidence. Note, however, that in the Pigeon Point occurrence, in the Bushveld, and in others, a large amount of truly liquid granitic magma was produced. Movements of flow occurred, so that intrusive contacts were formed and dikes injected.

There are indications that quartzose material is often very refractory toward solution and assimilation in a foreign magma, and that other rocks yield much more readily. Collins, in the article referred to,[4] expresses his views on the quantitative results of assimilation as follows: "Magmatic assimilation has long been accepted as an operative geological process. . . . . At present, investigators of

[1] *The Sudbury Laccolithic Sheet*, p. 774.

[2] *Secondary Origin of Certain Granites*, p. 213.

[3] W. H. Collins, "Onaping Map Area," *Geological Survey of Canada Memoir 95* (1917), pp. 60–62.

[4] "Onaping Map Area," p. 58.

the problem are more concerned with its quantitative aspect. To what extent has magmatic assimilation ever been effective?"

He then describes the evidence in one part of his area, and concludes: "If the view expressed above is correct, over an area of many square miles—at least 50—in this locality, the batholithic magma absorbed a thickness of schists measurable in hundreds if not thousands of feet."

On the subject of transfer by magmatic emanations and on assimilation a large number of other authors might be quoted who express views similar to those given. Space requires, however, that we pass on to other phases of the subject.[1]

THE HEAT SUPPLY IN ASSIMILATION

Several instances of large-scale assimilation have been given. Strictly, assimilation and differentiation are separate processes, but a number of geologists have denied the possibility of any significant amount of assimilation, and have attributed to differentiation practically all the variations of magmatic composition that we find. It is logical, therefore, to include assimilation in our discussion.

Harker has been greatly opposed to the conception. Curiously, some of the best examples we have are described by him in his "Tertiary Igneous Rocks of Skye," and are attributed to this process, but such action is regarded as exceptional, and rarely possible except when the assimilating intrusive follows its predecessor so closely that the heat of the first has not been dissipated.[2] The evidence for such a generalization, however, does not appear to be conclusive. Harker's difficulty in admitting such a process is based chiefly on apparent lack of adequate heat supply, and is stated as follows: "The insuperable objection to any such theory is that it demands an enormous amount of heat to raise the solid rocks to the point of melting and to melt them, and no source for this heat is indicated."[3]

[1] A paper by Sederholm ("On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland," *Commission Géol. de Finlande, Bulletin 58* [1923], Part 1), should be especially mentioned, both for its valuable discussion of granitization and syntexis, and for its extensive bibliography of articles on related subjects.

[2] A. Harker, *The Natural History of Igneous Rocks* (1909), pp. 356–59.

[3] *Ibid.*, p. 339.

This may not be so serious a difficulty as Harker supposed. A number of suggestions have been made which tend to lessen it. Several writers have favored the idea that at volcanic vents combination of oxidizable gases issuing into the air develops much heat; the difficulty is that the heat is not developed where it is required. A more important source is indicated in the theory that supposes surface rock, containing large amounts of Fe_2O_3 produced by weathering, has collapsed into the orifice and has been engulfed by the magma. This acts as a carrier of oxygen to greater depths, and the results may be important. Also, streaming of gases from lower levels to the surface tends to maintain surface temperatures. For plutonic intrusives it has been held that the great quantities of volatiles that pass through the walls transfer vast stores of heat from the magma, and may bring the temperature of the wall rocks nearly to fusion. This seems likely to be a very effective process.

There is a possibility, too, that exothermic chemical reactions within the system itself may play a part. In many respects magmas are very different from the so-called "dry" melts of the laboratory. With their great content of volatiles they should be regarded as highly complex chemical systems, whose equilibrium is responsive to every varying condition they encounter in their transfer from the depths of the earth to the upper lithosphere. We have some qualitative knowledge of the chemical nature of the volatiles; what little quantitative knowledge we have applies almost wholly to surface lavas at a stage just a little prior to solidification, for it is only then that collections can be made. It is surely unjustifiable to assume that this information serves as a reliable basis of estimate of the relative or absolute concentration of volatiles in a freshly risen lava during a great volcanic eruption, and still less to the concentration at profound depths. Even if all this information were available, however, we should still have little knowledge of the form of combination of the volatiles with each other and with the non-volatiles, nor how this is affected by profound changes of pressure and partial escape of volatiles during the ascent. We know, however, that rearrangements must continually take place.

It is perhaps not sufficiently appreciated that in any homogeneous liquid or gaseous solution made up of mutually reactive in-

gredients every change of condition changes the inner equilibrium. Increase or decrease of external pressure, raising or lowering of temperature, change of concentration of one or several components, affects quantitatively the amount of every compound in the solution. Each reaction is accompanied by a heat effect, large or small, positive or negative. It is impossible to say what the net thermal effect will be, but, realizing these potentialities, we are in a position to understand that if igneous phenomena seem to demand a supply of heat for which we can find no other source, the door is not shut against entertaining the notion that reactions in an ascending magma may at times be highly exothermic.

PROCESSES AT NOVARUPTA

The Katmai region presents an example of assimilation on a large scale, for which the necessary heat may conceivably have been derived from several sources. This is found in the parasitic dome of Novarupta. Some of the phenomena to be seen here have been described in a previous article.[1] On my second visit to the region, much more information was obtained, and this will appear in a later paper. At this time I shall simply insert a photograph (Fig. 13) showing the typical effects, and give a few words of explanation. The photograph shows partly melted xenoliths of basic rock which have been softened to such a degree that they yielded to movements of the lava and were pulled out into bands or *schlieren*. Later stages show complete melting of the groundmass of the basic material and corrosion of the phenocrysts, and finally the basic and acid magmas are completely united. The proportion of dark bands to white rhyolite in the dome was estimated as between one-fifth and one-third.[2]

Heat development may in this case be partly attributable to reduction of higher oxides of iron in the xenoliths, but it does not seem probable that this was of large magnitude. There is, in fact, no evidence of such reduction. The xenolithic material, before en-

[1] C. N. Fenner, *The Origin and Mode of Emplacement of the Great Tuff Deposit of the Valley of Ten Thousand Smokes*, published by the National Geographic Society of Washington, 1923. See especially pp. 55 ff.

[2] The quantity of xenolithic material is probably a little less than these figures indicate, as the dark bands themselves contain a little admixed rhyolite.

gulfment, was andesite, apparently not greatly weathered, and the state of oxidation of the iron appears the same during all stages of digestion.

There are several other phenomena of interest at Novarupta. In spite of the explosively destructive character of the outburst a little evidence was found, leading to inferences regarding the ability of the volatile gases to abstract and carry away with them ingredients not themselves volatile. In the thick beds of ejected pumice

FIG. 13.—Typical block of Novarupta lava, showing bands of white rhyolite alternating with dark-brown basic material formed from xenoliths. At the point of the pick is an undigested xenolith. (Photograph by C.N.F., 1923.)

certain strata are deeply colored—crimson, yellow, or yellowish brown. This is due to a mere staining of the pumice with iron oxides, but the lumps are deeply impregnated. Presumably the iron was deposited by the little residual gas that oozed out subsequent to the first violent inflation of the pumice. It is remarkable that some strata show this staining and others, above and below, are free from it.

Another phenomenon is in some ways more striking. Among the various kinds of xenoliths in the pumiceous strata are occasional small blocks of dense, somewhat crumbly rock, bleached to a dull white or pale sulphur-yellow color. Several of these were collected.

Under a binocular magnifier of moderate power some show glassy phenocrysts of feldspar in a finer groundmass, and suggest a porphyry; others are fine-grained throughout.

One of the porphyritic specimens, No. 415, was sliced for microscopic examination, and also a chemical analysis was made. The thin section is very curious. It is made up largely of the outer shells of fresh-looking phenocrystic and lathlike feldspars, with interiors replaced by isotropic glass. A little quartz and one or two small crystals of an altered ferromagnesian mineral, probably biotite, are also present. The feldspathic shells are thin, but each is fairly continuous, and both twinning and zoning are plainly visible. The appearance suggests an andesite or a fine-grained diorite as the original rock.

The analytical results are equally curious, and are given below. Column I shows the constituents found, and II is a recalculation to 100 per cent with the volatiles omitted.

	I	II
SiO_2	78.00	85.03
Al_2O_3	7.18	7.83
Fe_2O_3	.25	.27
FeO	.31	.34
MgO	.34	.37
CaO	2.14	2.33
Na_2O	2.08	2.27
K_2O	.56	.61
H_2O+	2.35	.....
H_2O-	4.90	.....
TiO_2	.86	.94
MnO	.01	.01
BaO	.00	.00
P_2O_5	.10	.....
Cl	.77	.....
SO_3	.05	.....
	99.90	100.00

C.I.P.W. symbol = 1. 2. 3. 4.

Especially significant are the large amounts of H_2O and Cl, and the great unlikeness in composition to any normal igneous rock. There has evidently been a selective abstraction of ingredients.

One cannot say in just what manner this has been accomplished, or why, in a relatively few of the xenolithic ejecta, the effects have been so much more intense than in most. Possibly these specimens represent material which, before the outburst of Novarupta, overlay its site, and later were in such a position that they were exposed to blasts of concentrated hot gases.[1]

DIFFERENTIAL TRANSFER BY GASES WITHIN THE MAGMA BODY

Thus far the discussion on transfer by volatiles has dealt with the removal of material to regions altogether outside of the magma. There is another possible effect which is indicated by theoretical considerations; its quantitative importance cannot be evaluated for lack of data.

It is well known that many volcanic orifices discharge gases continuously for long periods. The outflow varies in quantity from scarcely perceptible exhalations to those manifestations in which violent eruptive activity continues for several years. In the latter instances the outpouring of gas must be exceedingly great. The fundamental conditions which give rise to these effects are practically unknown. Suess has supposed, indeed, that the driving force at volcanoes is steam and other gases emitted from the deep interior of the earth and melting and stoping their way upward, and he likens the present state of the earth to an intermediate phase between the free gas-emission stage of the sun and the extinct stage of the moon.[2] Without attempting to determine the source from which the gas emanates, however, we may favorably entertain the tentative view of most volcanologists that there is probably a streaming of gases through the magma reservoir from lower levels toward the surface, some of it escaping through volcanic conduits and some penetrating the rock walls, and we may inquire into the consequences of this conception.

[1] Chlorine and chlorides have been utilized in a number of laboratory and technical processes for volatilizing iron and various other metals. See, for example, J. C. Hostetter, H. S. Roberts, and J. B. Ferguson, "The Volatilization of Iron from Optical Glass Pots at High Temperatures," *Journal of the American Ceramic Society* Vol. II (May, 1919), p. 356. In the procedure described here the amount of iron in the clay pots was reduced by chlorination by more than half, and titanium also was removed.

[2] E. Suess, *The Face of the Earth* (English translation, 1909), Vol. IV, pp. 548 ff. and 559.

The equilibrium in a mixture of gases is dependent upon the temperature and pressure. The differences of pressure between the lower and upper levels of a large magma body must be very great. In the ascent of a gas bubble, reactions among its constituents will ensue, of such sort as to increase the molecular numbers. Reactions with the surrounding magma will likewise take place. Some substances will be given up to the magma and others taken into gaseous solution. When the gas finally escapes, its composition will be different from what it was at lower levels. The effectiveness of magmatic gases as agents of differentiation, therefore, lies both in their ability to carry away material entirely when they escape, and in their ability to make selective transfer of material from lower to upper levels.

PERRET'S OBSERVATIONS ON GAS DISCHARGE AT VESUVIUS

The best picture of explosive volcanic activity seen at close range ever recorded is probably that of Perret,[1] of the Vesuvius eruption of 1906. The amount of gas poured out for several hours was so stupendous as to be inconceivable. From his observations here Perret declares "gas is the active agent and the magma is its vehicle,"[2] and "It was the revelation of this preponderance of the gaseous element over the solid matter emitted therewith that so deeply impressed upon the writer the conviction that gas is the principal eruptive element and that all else is accessory. In his opinion, failure to realize this basic truth has been the cause of many errors in the conception of volcanic phenomena."

Perret's observations were made on the mountain and as close to the orifice as possible with any regard to safety. It is significant, with respect to our small knowledge of what actually occurs during a violent eruption, that a number of experienced volcanologists who observed the course of events from more distant points were almost unaware of this tremendous gas discharge, the summit of the mountain being hidden from view by dust clouds.[3]

[1] *The Vesuvius Eruption of 1906*, Carnegie Institution of Washington, Publication No. 339, 1924. See especially pp. 43 ff.

[2] *Ibid.*, pp. 59 and 80.

[3] In a review of Perret's monograph, I. Friedlaender (*Zeitschrift für Vulkanol.* [February, 1926], Band 9, Heft 4, p. 214), makes a calculation of the quantity of gas

LACK OF DIFFERENTIATION IN MANY FIELD OCCURRENCES

We have now reviewed some of the evidence indicating the importance of other processes than crystal separation in differentiation. Let us take up a consideration of difficulties that the theory of crystallization differentiation has to meet if it is conceived to be the sole process.

A difficulty likely to appear of special importance to geologists who have studied intruded bodies of great dimensions in mountainous countries, where the vertical range of exposures is large, is that frequently they give no hint of gravity separation. Pirsson, with his wide experience in the field, expressed this view twenty years ago.[1] He recognized that the laccoliths of the Highwood Mountains furnished some evidence that gravity had probably been a factor in the formation of bottom layers of mafic rock, but in discussing Schweig's suggestion that differentiation may be caused by the crystallizing out of definite minerals and the separation of such crystals through gravity, he says:

> It seems rather difficult to accept this view in the simple form thus stated, as experience does not seem to show that there is the settling out of crystals through a greater specific gravity as postulated. Nothing is more common than to observe great vertical thicknesses of igneous rocks exposed by erosion, often for several thousand feet, and find that they are of uniform character throughout from top to bottom. This the author has seen repeatedly, and many instances will occur, no doubt, to all petrographers. Indeed, the author has never seen any instance where a direct proof of such settling could be observed, though a few are claimed in the literature. On the other hand, a priori, it would seem to be a very natural result, and where it does not happen its failure must be attributed to the viscosity of the mother liquor in which the crystals are formed. Yet it is evident that the mother liquor cannot be so viscous as to prevent molecular flow, otherwise crystallization could not take place. These are perplexing questions, and our knowledge of the physical properties of molten magmas is as yet far too incomplete to enable us to answer them with certainty.

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evolved. The figures are necessarily only approximate, but assuming that the outflow of gas continued for twenty hours, with a velocity of 500 m. per sec., from an orifice of 500 m. diameter, Friedlaender finds that the quantity was equivalent to 1.75 cu. km. of liquid water, while the total solid material is calculated to have been only 0.25 cu. km.

[1] L. V. Pirsson, "Highwood Mountains, Montana," *U.S. Geol. Survey Bulletin 237* (1905), p. 184.

Though we are now inclined to ascribe to the effects of crystal settling more instances than Pirsson recognized, we still must admit the general truth of his observations as relating to field occurrences. No wholly satisfactory explanation has yet been found. Conclusions regarding the settling of crystals, based on laboratory experimentation, require to be tested by further field observations. An important fact of field observation is that in very many instances the crystals do remain suspended, and we may raise the query whether conditions in a primary magma chamber are not likely to be of a more turbulent character, and hence more likely to lead to this result than in satellitic intrusions.

In this connection we may recall the feldspars of oscillatory zoning found in innumerable lavas, implying that in primary magma chambers crystals have been in suspension for prolonged periods during which many oscillations of composition occurred.

It might be said that those bodies in which no evidence of crystallization differentiation is to be seen indicate that no sort of differentiation has been operative, but when it is found that such bodies are members of regional differentiation series, this view can hardly be maintained unless auxiliary hypotheses be made. If it be said that differentiation has not affected them since their departure from the parent body and emplacement in their present position, a stronger case is presented, but the principal difficulty is not solved, namely, that with all the conditions as favorable as possible, so far as we can see, for crystal settling in the body after emplacement, this settling did not occur.

DIFFERENTIATION OF THE PALISADE DIABASE

The well-known Palisade diabase sill[1] in New Jersey and New York offers an almost demonstrable example of gravity separation of crystals, but there are some features worthy of discussion.

Near the bottom of this great sill a "ledge" or stratum of olivine-diabase, 10–20 feet thick, may be found exposed at intervals for a distance of 20 miles. The olivine-rich ledge is not directly at the

[1] The description of this is based on J. V. Lewis's account in the *Annual Report of the State Geologist of New Jersey for 1907*, pp. 103–37, supplemented by correspondence with Professor Lewis. In addition, I have examined the relations a number of times in person.

base, but is separated by 40–60 feet of more normal diabase, containing scattered olivines. The contact between the two is usually sharp. The ledge contains about 15 per cent of olivine, together with feldspar, augite, and a little iron ore. The upper contact again is usually sharp, and above comes the great body of diabase, from which olivine is entirely absent. In this upper portion the mafic silicate is prevailingly augite, though occasionally there is a little biotite. The other essential constituents are feldspars (both plagioclase and orthoclase), ores, and quartz; the last often in graphic intergrowth with feldspar.

Above the olivine ledge the great thickness of rock is differentiated to a much less degree than is the olivine layer, though in a general way the uppermost portions are notably richer in sodic plagioclases and orthoclase, while the lower contain much augite and the more calcic plagioclases.[1]

The sill, therefore, exhibits two striking features: (1) Gravitative separation of crystals is clearly shown; (2) the main separation began and ceased abruptly.

A reasonable explanation of these features is that during the formation of the "olivine ledge" the crystals separating were predominantly heavy ferromagnesian minerals, and these easily settled by gravity, carrying down some feldspar. Later, the crystallization of olivine ceased, and a greater proportion of feldspar crystallized out, which was of less specific gravity than the earlier feldspar because more sodic. Becoming attached to crystals of augite and magnetite, it tended to buoy them up. Also, the proportion of crystals to liquid increased, and free settling was interfered with. Now the question presents itself, does this represent the stage at which crystal settling usually stops, or, if not, what different conditions are present in other cases which allow it to proceed further? The Palisade sill is several hundred feet thick, and it seems that cooling should have been very slow.

The variation diagram of the Palisade sill is shown in Figure 12. The rather random distribution of indicative points is in great contrast with their alinement in the Katmai diagram.

The close adherence of points in the Katmai diagram to a linear

[1] J. V. Lewis, *op. cit.*, p. 132.

relation indicates that a single process of differentiation prevailed here, little interfered with by other influences, yet when we examine the thin sections of the rocks we find that the intratelluric phenocrysts simultaneously suspended in the magma are minerals of very different specific gravities. Pyroxenes, magnetite, plagioclase, and (in some) quartz occur both in separate crystals and in glomeroporphyritic groups. It was through the failure of crystals to settle in the Palisade sill that we found the explanation of early cessation of differentiation. Why did not the processes restraining differentiation in the Palisade sill accomplish the same result in the Katmai magma chamber? We begin to suspect that, whereas in the Palisade sill gravity separation of crystals was the principal cause of differentiation, and most of the differentiation stopped when the crystals ceased to settle, in the Katmai series differentiation was due to other causes, and failure of crystals to settle had little effect.

THE RELATION OF OLIVINE TO MICROPEGMATITE

In Bowen's development of his theory he starts with a magma of basaltic composition in which the silica content is not sufficient to satisfy the full requirements of feldspars and metasilicate minerals, and very ingeniously conceives a process by which a highly siliceous magma may eventually be formed. This is based primarily upon the fact, experimentally determined by himself and Andersen, that in binary and ternary systems crystallization of olivine extends into a field having an excess of silica. He supposes that in the crystallization of a basic magma there is a crystallization of olivine, as in artificial melts, and that the crystals settle out by gravity, leaving a liquid with a small excess of silica. Then it is easy to see that if, at a later stage, metasilicates and feldspars crystallize out in a normal manner, and settle similarly, the liquid becomes continuously enriched in silica. He suggests that in the later stages biotite performs a function similar to olivine, but the separation of biotite would carry with it too great a proportion of potash, as analyses of biotites show, and would cause the more siliceous magmas to become poorer in potash instead of richer. The separation of hornblende and magnetite, however, might give the required results.

To the action of olivine in the manner indicated he ascribes the

very frequent occurrence of microgranitic (micrographic, granophyric, micropegmatitic) intergrowths of quartz and alkali feldspar of late crystallization in the interstices of diabase. He says:

> Diabases with micropegmatite interstices are very common. Sometimes the micropegmatite (granophyre) is separated as a distinct body, a granite, granodiorite, or quartz diorite in composition. This association is of fundamental importance to petrogenic theory and will be made the starting-point for a discussion of the geologic evidence supporting crystallization differentiation. . . . .
>
> The early formation of olivine brings about an excess of free silica if any process intervenes to prevent the resorption of the olivine by the liquid. The early formation of very calcic plagioclase brings about an enrichment of the liquid in albite if anything intervenes to prevent the continual alteration in the composition of the crystals by interchange with the liquid. Finally, the early formation of magnesia-rich pyroxene brings about an enrichment of the liquid in diopsidic pyroxene if similar conditions intervene.
>
> The sinking of crystals affords a means of continually separating crystals from the part of the liquid in which they formed, and is therefore a process which will give the results just outlined. If, therefore, the mixture of plagioclase and pyroxene referred to were cooled slowly and continued sinking of crystals occurred, the inevitable result would be a body consisting of calcic plagioclase, olivine, and magnesian pyroxene in its lower parts (i.e., of a gabbroidal nature) and of sodic plagioclase approaching albite, diopsidic pyroxene, and free silica in its upper parts (i.e., of a granitic nature), with various intermediate types in the intermediate layers.[1]

He says, furthermore, that "it is clear that the broad scheme is well understood and that crystallization is the sole control."

Crystallization of olivine extending into a field on the silica side of the metasilicate ratio produces free silica in the liquid, in the manner just indicated, but unless the liquid frees itself of the olivine crystals, they will in normal course react a little later with the liquid, and the silica excess of the liquid will tend to disappear. Among the reasons for questioning the explanation given, two may be mentioned here: (1) a doubt as to the quantitative adequacy of the process; (2) uncertainty as to whether the microgranitic interstitial filling of diabases, to which so much importance is attached, may not have another explanation.

With regard to the quantitative adequacy of the process it is pertinent to quote the conclusion reached by J. V. Lewis in his study

[1] N. L. Bowen, *The Later Stages of the Evolution of the Igneous Rocks*, pp. 17, 39.

of the Palisade sill. As he had no theory in mind, the opinion is unbiased. He says: "Considering the diabase as a whole quartz is a far more frequent constituent of the rock than olivine."[1] It appears from this that though the precipitation of olivine may have increased the amount of quartz, the greater part of the quartz would have appeared in any case.

The question as to the manner in which the micrographic intergrowths are produced requires discussion. Bowen's treatment passes over the differences of opinion regarding their origin and the great amount of work done in an effort to settle the question, and sets aside the opinion to which many able petrologists have come, that in basic rocks this peculiar intergrowth is of secondary genesis, rather than a primary magmatic product.

THE ORIGIN OF GRAPHIC INTERGROWTHS

Graphic intergrowths of quartz and feldspar, whether megascopic or microscopic, and whether in acid or in basic rocks, have been regarded by many as representing a eutectic, and this opinion has doubtless reacted favorably toward an acceptance of the idea that these intergrowths, when found in the interstices of diabases and similar rocks, represent the final consolidation of the residual liquid and indicate the manner in which a quartz-feldspar magma has been formed from a basaltic magma. In recent years the eutectic explanation has been accepted by many without question. It seems not to be realized how little direct evidence can be brought to its support.

Warren and Palache, in a description of the pegmatites of Quincy, Massachusetts,[2] state an opinion which seems to represent the true situation. They say:

> In fact, ... in graphic granites in general, there appear to the writers to be serious, if not fatal, objections to their being regarded as eutectic mixtures. The idea is at present little more than an interesting speculation suggested by a resemblance in the texture to that of known eutectics among metals and a crude approximation in a number of cases to constancy in chemical composition.

[1] J. V. Lewis, *op. cit.*, p. 124. Quantitative figures to show the greater abundance of quartz in the sill as a whole are given.

[2] *Proceedings of the American Academy of Arts and Sciences*, Vol. XLVII (1911), No. 4, p. 147.

We have little information as to the real cause of the formation of graphic textures. We know that in metallic alloys they are very closely connected with eutectic composition, so much so that graphic texture has come to be regarded as almost synonymous with eutectic texture. It is hardly allowable, however, to transfer the idea, without further evidence, to silicate melts, for in slags and other artificial melts, even when of eutectic composition, well-developed graphic textures are exceptional.

The real characteristic of this texture is a certain remarkable orientation and configuration of crystal intergrowths. Within our limited experience, these appear in best development as the result of simultaneous crystallization of two metals in fixed proportions at an invariant point, but we do not know why this should be true, and we do not know but that a variety of conditions, some of which may not have any relation to eutectic crystallization, may lead to similar crystal orientations.

It is at least known that graphic intergrowths may result from the breaking down of solid solutions which are homogeneous at the temperature of crystallization. An example is the "eutectoid" texture of iron and cementite, formed by the unmixing of martensite. The oriented graphic texture appears, but the conditions of formation have no recognizable relation to those in eutectiferous liquids.

If, however, the eutectic proportions are regarded as so generally in evidence that they should be considered the prime essential, then the essential factor is a condition which is not present during the cooling of plutonic magmas; for if the magmas of plutonic rocks have the constitution usually attributed to them, the presence of low-melting components ("volatiles") prevents this condition from being realized. The eutectic temperatures of such solutions lie below the freezing-point of water. At all higher temperatures, from the beginning of crystallization downward, the process is simply the ordinary process of deposition of crystals from a solution: a concentrated silicate solution at high temperatures, passing at lower temperatures by insensible gradations into a solution in which the volatiles predominate, and eventually reaching the condition where gas pressure expels the final attenuated solutions. No stage can be recognized at which eutectic conditions hold, nor is there any apparent

reason, either from theory or by analogy with metals, why a eutectic texture should be characteristic of any particular stage.

If the eutectic idea were the true explanation, seemingly this texture should be the common result of final crystallization in many rocks of not too fine grain. The interstitial micropegmatitic intergrowth found in small quantity in diabases should reappear in greater quantity and of the same composition in diorites and andesites, and should form nearly the whole mass of granites and rhyolites.

As regards the supposed constancy of the quartz-feldspar proportions in graphic granite, probably most petrologists have seen specimens showing typical textural characteristics, yet obviously varying widely from the assumed proportions. Vogt, especially, has urged the eutectic interpretation for graphic granite, but his reasons seem equally applicable to the product of final crystallization of granites in general, which usually have not the graphic texture. On the contrary, it is generally believed that quartz with but little feldspar is the final mineral to crystallize in granites. Also, it is well known that many pegmatite veins pass gradually into veins of nearly pure quartz. These facts are not at all in accord with the eutectic conception.

Bastin[1] has made a careful study of Maine pegmatites with respect to the eutectic conception. The evidence is regarded as unfavorable to the theory. In some of the occurrences studied "the graphic granite was certainly not the last crystallization from the magma."

Vogt[2] has placed the eutectic composition of graphic granites, micropegmatites, and microfelsites at about 74 per cent feldspar to 26 per cent quartz, and he ascribes approximately the same proportion of quartz to feldspar in the glass base of acid vein- and surface-rocks. The soda rhyolite of the last Katmai eruption probably corresponds as closely in composition to a quartz-feldspar eutectic as igneous rocks ever do (see No. 175 in table of norms, and petrographic description), but the ratio of 57.41 feldspar to 38.52 quartz shown by calculation is very different from Vogt's ratio.

But if the graphic texture in pegmatites is not due to eutectic

[1] E. S. Bastin, "Origin of the Pegmatites of Maine," *Journal of Geology*, Vol. XVIII (1910), p. 312.

[2] J. H. L. Vogt, *Silikatschmelzlösungen* (Christiania, 1904), Vol. II, p. 123.

crystallization, to what is it to be ascribed? To this again a complete answer cannot be given, but evidence is at hand indicating processes very different from eutectic crystallization. Schaller,[1] in a recent article, has given reasons for believing that certain pegmatites studied, and probably many other pegmatites, have been formed by prolonged circulation of mineral-bearing solutions, and that their minerals are due to a series of paragenetic transformations. Graphic granite was one of the earliest products, but, he states:

> That the graphic granite itself was the original rock formed by the solidifying magma is not at all certain. The writer is inclined to the belief that it, too, is the result of another type of replacement of a still earlier formed rock. The evidence at present suggests that an orthoclase rock was the one originally crystallizing from the injected magma; that the orthoclase later reverted to microcline; and that the physical effects resulting from such an inversion facilitated the entrance of replacing solutions which deposited quartz and formed the graphic granite.[2]

In the view of many petrologists, the micropegmatitic texture, as well as the coarser texture of graphic granite, is often of secondary origin. In preceding pages we have seen that in the granitization of quartzites micropegmatitic intergrowths are so frequently formed that they have been considered by Coleman, Collins, and others as almost diagnostic. Likewise, a secondary origin for the micropegmatite in the interstices of basic igneous rocks has been held. It is attributed to processes of endomorphic transformation active in igneous bodies during the later stages of cooling, during which the final fluids are expelled from the consolidating rock. An explanation involving such a deuteric origin has been applied to chloritization, serpentinization, uralitization, propylitization, albitization,[3] etc.,

[1] W. T. Schaller, "The Genesis of Lithium Pegmatites," *American Journal of Science*, Vol. X (1925), p. 270.

[2] Another able discussion of pegmatites is that of F. L. Hess, "The Natural History of the Pegmatites," *Eng. and Min. Jour. Press*, Vol. CXX (August 22, 1925), No. 8. Hess brings forward many facts to demonstrate the replacements effected by long-continued passage of solutions, for which a gaseous condition is favored. Similar processes are believed by Hess to have effected contact metamorphism in limestones and other replaceable rocks, and the point of view is closely similar to that of Lacroix, Adams and Barlow, and others previously quoted.

[3] Henry Dewey and J. S. Flett, in "British Pillow Lavas and the Rocks Associated with Them," *Geological Magazine*, Vol. VIII (1911), pp. 202–9, 241–48, give an instructive discussion of albitization of basic feldspars in spilitic rocks, and attribute it "to a

and may be equally applicable to the formation of the microgranitic texture.

A detailed discussion of these matters appears in a contribution by Sederholm[1] in which about eighty pages are devoted to such textures.

The memoir contains a valuable summary of the work and conclusions of the many petrologists who have worked on myrmekitic textures.[2] Not all are agreed in their interpretations, but probably the majority regard the structures as secondary, which is the view of Sederholm. In his concluding remarks[3] he attributes both albitization and myrmekitization to the action of superheated waters:

> As to the myrmekitization, most of the different theories are of some value, at least in the elucidation of some minor points, though none of them give a complete explanation of the whole process. This is, as Tronquoy has remarked, a special case of albitization. But the latter process, again, is only one of the special cases of the changes which rocks undergo when they are percolated by superheated water carrying in solution a number of different matters, many of which are extracted from adjacent rock masses, and by gases.

In view of the many modes of occurrence of micropegmatite, and especially in view of the fact that many petrologists regard as secondary the micropegmatitic textures in basic rocks that Bowen makes the starting-point of his theory, one is hardly prepared to accept without further evidence the conclusion that these intergrowths of quartz and feldspar are to be regarded as representing the composition attained by the residual magma in the normal course of crystallization, nor to look upon granitic magmas as this same liquid separated from the first-formed crystals.

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pneumatolytic change that affected the spilites very shortly after their effusion." Harker (*Petrology for Students* [Cambridge, 1919], p. 192), expresses a similar view, ascribing the albitization in spilites to "a late stage in the consolidation of the rocks."

[1] J. J. Sederholm, "On Synantetic Minerals and Related Phenomena," *Commission Géol. de Finlande, Bulletin 48*, 1916.

[2] Sederholm, departing from the usage of most writers, restricts the term micropegmatite to intergrowths of orthoclase and quartz, and uses the word myrmekite for "an intergrowth of plagioclase and vermicular quartz" (p. 134). It is plain from the descriptions and illustrations that a great part of the intergrowths in basic rocks described as micropegmatite by most writers in this country would be classed by him as myrmekite.

[3] *Op. cit.*, p. 140.

NATURE OF THE RESIDUAL LIQUOR LEFT BY CRYSTALLIZATION

We may approach this matter from another direction. It has been considered important evidence, in confirmation of the theory of differentiation by crystallization, that the residual glass left after the main crystallization of a rock has been found at times to be of more siliceous composition than the crystals. It has even been held that in general a parallelism may be perceived between the change of composition of residual liquid with advance of crystallization and the course of differentiation.

This parallelism and the support it is supposed to give to the theory of crystallization differentiation have been referred to by many writers, but there is a circuitous reasoning involved which affects the conclusions; for if it be assumed that the composition of the liquid is simply the result of crystallization, this automatically excludes other possible causes. The matter to be determined is involved in the postulates.

An assumption of this kind is justifiable when working with laboratory melts under conditions which exclude other processes, but it is not justifiable to assume that these conditions have prevailed in magma reservoirs. According to certain experiments of Lagorio,[1] if NaCl or KCl be added to a rock fusion in a crucible, there is brought about a very material change in the relative proportions of the various constituents. If such a melt should be partly crystallized, the composition of the residual liquid is attributable just as much to volatilization as to crystallization.

Likewise, if a volcanic eruption furnishes us a sample of rock in which intratelluric phenocrysts have developed, but which has been subject to other differentiative influences (not only volatilization but assimilation, mixing of magmas, and possibly unknown processes) we are not justified in saying that a trend of the residual liquid toward a granitic or other composition is the result of crystallization alone. It is quite conceivable that nearly the same changes would have been effected by some other process if no crystals had formed. In fact, if crystallization happens to proceed slowly, and other processes rapidly, the composition of the crystals follows, and

[1] A. Lagorio, "Ueber die Natur der Glasbasis, sowie der Kristallisationsvorgänge im eruptiven Magma," *Tscher. Mitth.*, Vol. VIII (1887), pp. 490 ff.

is a consequence of, the differentiation of the magma, and not the reverse. In whatever manner differentiation is brought about, the crystals deposited from the differentiating magma will respond in composition.

Before it is allowable to attribute differentiation to crystallization we have the difficult task of determining just what effects crystallization can accomplish. Queries must be answered as to whether the ratios of the whole assemblage of constituents, brought about by crystallization, are in agreement with the results of differentiation. We know that by crystallization an increase of the ratio of alkali feldspars to lime feldspars should be expected, but does this mean there is an increase in the ratio of alkali feldspars to other constituents, such as is characteristic of silicic magmas? What changes in the relative and absolute amounts of the various bases can be expected from crystallization? Do these changes correspond with those which actually occur in a differentiating magma? We have some information on these matters gained from artificial melts, and this will be discussed a little later. We have also a little information given by natural rocks, and this will be taken up now.

The main question is whether bodies of basaltic magma, by crystallization alone, tend toward a granitic residual liquid. The micropegmatitic material in quartz diabases has been held to be proof that they do, but we have seen that often micropegmatite is the result of other processes. We shall therefore try to select examples in which the influence of other processes is excluded. Surface basalts occasionally give favorable opportunities for such a study.

According to Bowen, the crystallization of a basaltic magma should normally lead to one of two not very different results, depending upon whether the excess of silica in the liquid, brought about by crystallization of olivine, does or does not later react with olivine. If, through settling-out of olivine or through quick cooling, reaction does not occur, the final result is a liquid consisting almost entirely of alkali feldspar and silica; if reaction does occur, the final liquid is essentially alkali feldspar.

Newton and Teall[1] describe basalts from Franz Josef Land which

[1] E. T. Newton and J. J. H. Teall, "Notes on a Collection of Rocks and Fossils from Franz Josef Land," *Quarterly Journal of the Geological Society*, Vol. LIII (December, 1897), p. 477.

consist of plagioclase (labradorite), augite, magnetite, and olivine in a finely crystalline or glassy interstitial groundmass. They investigated especially the composition of the groundmass in relation to the phenocrysts, and state:

> We are therefore able to draw the important conclusion that in a magma of the type to which these basalts belong—that is, a basic magma, poor in alkalies[1]—progressive crystallization leads to the formation of a mother-liquor poor in silica and alumina and rich in iron. . . . .
>
> The concentration of the iron, and, to a certain extent, magnesia, in the mother-liquor of basic magmas does not appear to have attracted the attention which it deserves. It shows that progressive crystallization in these magmas sometimes leads to a result the opposite of that observed in the case of intermediate magmas in which ferriferous compounds separate out during the early phases of consolidation.

They state also, with reference to magnetite:

> The feldspar and augite are as a rule remarkably free from inclusions of this mineral; which certainly does not, in these rocks, belong to the earlier phases of consolidation, as it does in so many rocks of intermediate composition. In many cases it is found only in skeleton crystals in the interstitial matter, ... and in some the iron oxides have remained wholly undifferentiated in a deep brown glass.

Washington[2] has observed very similar features in the Deccan traps, described as follows:

> What is of special interest, however, ... is the late stage of crystallization of the magnetite and of much of the augite. The rarity of augite and the practical absence of magnetite as inclusions in the feldspars, especially in those of ophitic types, as well as the progressive rarity of well crystallized magnetite with increase in glass content, together with a somewhat less well-marked decrease in augite as compared with feldspar as the rock becomes more glassy, point to the conclusion that nearly the whole of the feldspar crystallized first, followed by much of the augite (probably with a period of some simultaneous crystallization), while the magnetite belongs to the latest stage. It would follow that the glass should have a composition corresponding to a mixture of augite and magnetite.

Probably many petrologists have observed the brown color that the interstitial glass of basalts is likely to retain even when the rock

[1] Since the feldspar is labradorite, they apparently do not mean poorer in alkalies than most basalts.

[2] H. S. Washington, "Deccan Traps and Other Plateau Basalts," *Bulletin of the Geological Society of America*, Vol. XXXIII (1922), p. 765.

is almost wholly crystalline, and the dendritic magnetite that has frequently crystallized out of this last residue.

In a yet unpublished article, Washington,[1] describing the hyalodacites of Santorini, states similar conclusions: "Instances are accumulating of rocks in which much of the pyroxene belongs to the final stage of crystallization, and this is true also of magnetite, contrary to the well-known dictum of Rosenbusch."

The paper by Lagorio to which reference has been made contains the results of much work done to determine the nature of the glass residue of igneous rocks. Though his own experiments showed that the presence of alkaline chlorides caused differential losses, he does not seem to have realized the possible application of this to magmas, and he assumed that crystallization was the only factor to be considered. This affects his conclusions, but it may be worth while to quote his findings. He states: "The glass basis has in acid and in basic rocks almost the same silicic acid content as the total rock, in those of medium SiO_2 content (about 55–65 per cent) it is more acid than this; in very acid (quartz- and spherulite-bearing) it is more basic; in very basic, on the contrary, more acid than the total rock."[2]

An article by E. V. Shannon[3] gives a basis for comparison of the chemical composition of an intrusive diabase and its crystallization differentiate. The occurrence is one with which many Washington petrologists are familiar.

A thick intrusive mass of diabase of sill-like form covers a large area. A quarry has been opened near the base of the sill. The material exposed consists in greatest part of a fairly normal diabase, composed principally of pyroxene, plagioclase, iron ore, and a little biotite, together with quartz in small amount, intergrown as a micropegmatite with orthoclase. Mixed somewhat promiscuously with this rock is a rock of similar mineral composition, but of very coarse grain, in which large feldspars occur and augite blades occasionally

[1] H. S. Washington, "The Santorini Eruption of 1925." Paper presented before the Geological Society of America, December 28, 1925, and to be published in the *Bulletin* of the Society. Many references are cited.

[2] *Ibid.*, p. 521.

[3] E. V. Shannon, "The Mineralogy and Petrology of Intrusive Triassic Diabase at Goose Creek, Loudoun County, Virginia," *Proceedings U.S. National Museum*, Vol. LXVI (1924), art. 2, pp. 1–86, especially pp. 1–41.

attain 25 cm. in length and 3 cm. in width. This is termed diabase pegmatite, and

> occurs in irregular and generally rounded to lenslike masses, sometimes of considerable size, isolated in fine homogeneous grained rock, while elsewhere coarse-grained fabric forms small spots so thickly scattered as to make up approximately half of a hybrid mass of rock. Most of the larger masses, however, are tabular bodies which occur between parallel walls of the normal rock and appear to bear a truly intrusive relation to it. These vary up to 50 cm., or possibly in extreme cases to a meter in width.

This diabase pegmatite is regarded as younger than the diabase of normal grain, but is closely related to it genetically. It is believed to owe its peculiar features to concentration of volatile constituents, notably water, into segregated spots and masses which remained fluid after the main mass of the diabase crystallized, and in places were injected into fissures. Micropegmatite is described as a prominent constituent of this rock, and consists of both orthoclase micropegmatite and plagioclase micropegmatite. A third type of rock comprises masses with a similar coarse texture, but consisting in the main of albite and quartz.

> This type is considered to be in part an end differentiate of the coarse second type, and in part a hydrothermal alteration product. The masses of the third type contain small miarolitic cavities lined with contemporary crystals of quartz, albite, titanite, and diopside, usually also with a later series of minerals consisting of fine fibrous hornblende, epidote, chalcopyrite, and chlorite.

The conditions which gave rise to these types seem evident. After most of the magma had reached a solidified condition, a residual portion, which was rich in volatiles and should have had the chemical composition of a late crystallization differentiate, was forced into certain restricted spaces or formed dikelike intrusions in the main mass. There it, in turn, solidified, for the most part, and formed the diabase pegmatite, but the final attenuated fluids were compelled to move onward, and they gave rise to the pneumatolytically altered rock with its miarolitic cavities and replacement minerals. Specimens which I have collected show a notably greater abundance of micropegmatitic quartz and feldspar in immediate association with the miarolitic cavities, as would be expected if these intergrowths were of secondary origin.

For the present discussion the important feature lies in a comparison of Shannon's analyses of the normal diabase and of the diabase pegmatite. They are reproduced below:

	Normal Diabase	Diabase Pegmatite
SiO_2	51.56	52.94
Al_2O_3	13.81	14.80
Fe_2O_3	.96	.16
FeO	11.32	12.00
MgO	7.40	5.42
CaO	10.08	8.32
Na_2O	2.08	1.98
K_2O	.96	1.50
TiO_2	1.48	2.32
P_2O_5	.16	.28
MnO	.19	.24
Total	100.00	99.96

The two are remarkably alike in chemical composition, and it would be difficult to detect in the analyses any tendency toward the formation of a granitic magma, although it seems as if the essential conditions postulated as leading to that result were present. We seem to have here an excellent illustration of crystallization differentiation with "filter-pressing," except that the differences of composition effected were small and not specially in the direction of the production of granite.

The micropegmatitic interstitial filling of diabases has been regarded as strong evidence in support of the view that crystallization of a basaltic magma normally leads to a final differentiate of granitic composition. The various examples just presented indicate that in many cases, at least, the course of normal crystallization leads to a residue not at all similar to granite. These facts seem to require careful consideration.

THE ALBITE-ANORTHITE-DIOPSIDE DIAGRAM

Certain laboratory experiments on the course of crystallization of artificial mixtures have been adduced in confirmation of the theory of crystallization differentiation. The experiments are admirable in themselves, and bring out important principles in the be-

havior of silicate melts; nevertheless a doubt is felt as to whether these simple systems correspond closely enough to natural magmas to justify the far-reaching conclusions that have been drawn.

As an instance of this uncertainty we may consider for a moment the relations of quartz to the other minerals of a granite. At one time petrologists considered it very puzzling that quartz, the most infusible of the minerals of granite, should continue its crystallization longest, and should finally fill the interstices. Likewise, it has been noted that many granitic pegmatites pass outward into veins of nearly pure quartz. There is nothing in our experience with dry melts to lead us to expect such results. More recently the true nature of granite magmas has become somewhat better understood, and it is realized that the large content of water and other volatiles, especially in the later stages of crystallization, modifies the solubility relations to such a degree that the properties of aqueous solutions are almost as applicable as those of silicate melts. In magmas less siliceous than granites the properties of dry melts usually hold more closely, but we should recognize that caution must be used in all cases in applying in strict detail to magmas conclusions derived from dry melts.

J. W. Evans has recently said: "Any experiments in which the volatile constituents are not represented by amounts similar to those that are found in natural magmas must be inevitably misleading."[1] This is a strong statement, and I venture to think that it sounds stronger than was intended, but if it is interpreted to mean that the volatiles modify the relations to such a degree that careful consideration must be given in applying experiments on dry melts to natural magmas, we must agree.

In another respect, apart from the effect of volatiles, there may be a question of the applicability of conclusions derived from laboratory experiments. The albite-anorthite-diopside diagram has been used in illustration of the progress of crystallization in intermediate magmas. It has been shown that in this system crystallization

[1] J. W. Evans, in a symposium on the "Physical Chemistry of Igneous Rock Formation," presented at a joint meeting of the Faraday Society, the Geological Society, and the Mineralogical Society, October, 1924, and reported in *Transactions of the Faraday Society*, Vol. XX (April, 1925). Many other speakers emphasized the importance of volatile substances in magmatic processes.

gradually eliminates anorthite and diopside from the melt, and the final result is a liquid containing about 97 per cent albite to 3 per cent diopside. Diopside ($CaMgSi_2O_6$) is considered representative of the metasilicate minerals (pyroxenes and amphiboles), and it is concluded that in natural magmas crystallization would similarly eliminate anorthite and pyroxenes or amphiboles.

A criticism is that this three-component system is much more simple than the multi-component magmas, even disregarding the volatiles, and, more specifically, that in an important respect diopside can hardly be taken as representative of pyroxenes and amphiboles. In the albite-anorthite-diopside system the elimination of anorthite and diopside results pretty directly from the fact that the melting-point of albite (about 1100°) is much lower than those of anorthite (1550°) and diopside (1391°). In natural magmas the pyroxenes and amphiboles contain a large amount of iron. There is uncertainty as to the quantitative effect this has in lowering the melting temperature, but Doelter's *Handbuch*[1] states that a content of $CaFeSi_2O_6$ added to diopside lowers the melting-point considerably, and that hedenbergite shows a melting-point of 1100–1160°. A lessened melting-point tends to change the eutectic ratio between albite and pyroxene and modify the characteristics of the diagram. It is not unreasonable to suppose that instead of only 3 per cent diopside in the final solution there would be 20 or 30 per cent of a low-melting iron-bearing pyroxene. Until the matter is experimentally determined, only a guess can be made, but it does not appear justifiable to regard diopside as truly representative of the metasilicates of magmas.

Without going further into this, let us examine some of the characteristics of the experimental systems.

The three principal systems used by Bowen in elucidating his theory are diopside-forsterite-silica, anorthite-forsterite-silica, and albite-anorthite-diopside. The first two are used in illustrating certain principles, especially the production of an excess of silica in the residual liquid by the crystallization of forsterite; the third is regarded as corresponding closely in essentials to the later stages of crystallization, and we shall select this for discussion.

[1] C. Doelter, *Handbuch der Mineralchemie* (1914), Vol. II, 1st half, p. 579.

Figure 14 shows the albite-anorthite-diopside system, as represented by Bowen,[1] with certain additions derived from his determinations. As this is strictly a three-component system, it is conveniently represented by a three-co-ordinate diagram. If a fourth component were added it would be necessary to use a solid model for representation, and more components would be beyond the possibilities of geometric representation.

The diagram is divided into two main fields by the boundary curve, *TSRFGHIKL*. Any melts of a composition represented by a point above the boundary curve will deposit on cooling diopside as the first mineral; any point below will give an albite-anorthite solid solution; along the boundary curve diopside and plagioclase will crystallize simultaneously.

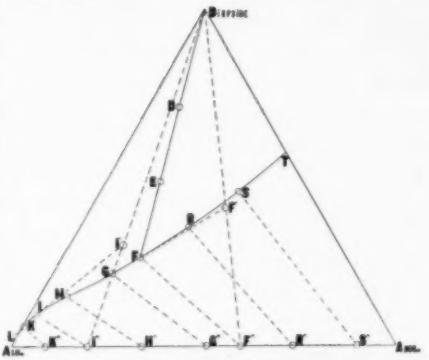

FIG. 14.—The albite-anorthite-diopside system on a three-co-ordinate diagram; adapted from N. L. Bowen.

If we start with a composition represented by *D*, the crystallizing-out of diopside will cause the composition of the liquid to change along the line drawn from the diopside apex through *D*, or *DEF*. At *F* the crystals of diopside are joined by crystals of albite-anorthite of a composition *F''*. The gross composition of the crystal mixture is found by drawing the tangent *FF'* to the boundary curve, and intersecting it with a line drawn from *F''* to the diopside apex. *F'* then represents the composition of the first crystals deposited, under equilibrium conditions, in a liquid of composition *F*.

If we suppose crystals to be removed as soon as formed, the composition of the liquid will move along *FGHIK*, and finally reach the albite-diopside eutectic at *L*. The composition of the eutectic is not exactly determinable because of experimental difficulties, but is placed at approximately 97 Ab 3 Di.

[1] N. L. Bowen, "The Later Stages of the Evolution of the Igneous Rocks," *Journal of Geology, Supplement*, Vol. XXIII (1915), No. 8, pp. 33 ff.

If diopside is taken to be representative of the ferromagnesian minerals, we seem to see how a mixture containing large amounts of ferromagnesian minerals and a large ratio of anorthite to albite may, by removal of crystals alone, pass to a nearly pure albite liquid; and if we suppose that at the same time silica, set free by early crystallization of olivine, has been accumulating in the liquid with the albite, the final liquid seems to correspond satisfactorily to the composition of granite or rhyolite.

There are, however, less obvious results derivable from the diagram, which lead to reflection.

At *D* the composition is: An, 8 per cent; Ab, 21 per cent; Di, 71 per cent; in a total of 100 per cent, or An, 8 kg.; Ab, 21 kg.; Di, 71 kg.; in a total of 100 kg. At *F* we have for the residual liquid, An, 8 kg.; Ab, 21 kg.; and Di, 10.3 kg.; or a total of 39.3 kg. By the time *H* is reached, we have 14.2 kg. Ab, 1.3 kg. An, 2.8 kg. Di, or a total of 18.3 kg. of liquid, and at *I*, 11.0 kg. Ab, 0.17 kg. An, 1.1 kg. Di, or a total of only 12.3 kg. of liquid out of the 100 kg. with which we started.

The composition of the crystals formed at *I*, as nearly as may be determined by geometric construction, is represented by *I'*, or 56 per cent Ab, 14 per cent An, and 30 per cent Di, while the liquid is 89.4 per cent Ab, 1.4 per cent An, 9.2 per cent Di, that is, the crystals contain very much more anorthite and diopside than does the liquid, and this is necessarily true at all points along the boundary curve. The application of this is as follows: From the point *I* to the final eutectic *L*, geometric construction is not sufficiently exact to determine the composition of the crystals deposited by a given liquid, but at *I*, with only 12.3 per cent of the original liquid left, the crystals deposited contain approximately 30 per cent diopside, an amount large enough to be easily detected with the microscope. Before we reach the composition on the diagram corresponding to some rhyolites, in which the amount of ferromagnesian minerals deposited in the early stages of crystallization is so small as to escape notice, the quantity of residual liquid must be decidedly less than 12 per cent of the original magma. Are the large rhyolitic extrusions and the large granitic batholiths to be considered such a very small percentage of a basaltic magma from which they were derived as is indi-

cated? One feels a reluctance in accepting this conclusion without more tangible evidence. To me it seems better to await further information before forming a definite opinion as to the origin of the great granite masses of the earth.

The diagram indicates that magmas of intermediate composition should be formed in much larger amount than the more siliceous differentiates. In view of this, the relations in many diabase-granophyre or gabbro-granophyre composite bodies which have been ascribed to crystal settling are puzzling. We find basic rock below and granitic rock above, as required, but in some of the bodies in which the antipodal development is best exhibited no large intermediate bodies of andesite or diorite are evident, and even in the small transition zone, the rock, as a rule, shows abnormal characteristics. It does not look like an ordinary andesite or diorite. With respect to quantitative representation in a more general sense the same observation regarding the deficiency of intermediate types sometimes applies. Teall has referred to "the sharp separation of basalt and granophyre, which is so striking a feature of the Brito-Icelandic province."

Another important result may be derived from the diagram. We have seen that in the Katmai diagram the distribution of indicative points is almost linear. Will removal of crystals give such a result? From the albite-anorthite-diopside diagram we may calculate the variation of SiO_2, Al_2O_3, CaO, MgO, and Na_2O during the course of crystallization, and plot them upon a two-co-ordinate diagram. The results of such a calculation are shown in Figure 15. In this any given composition, such as is represented by the point *D* in Figure 14, becomes, in Figure 15, a series of four points, representing, respectively, Al_2O_3, CaO, MgO, and Na_2O, plotted against SiO_2, and the variation in composition along the line *DEFGHIL* in Figure 14 is shown by the four lines of Figure 15. Then this becomes comparable with the Katmai diagram.

It is obvious that the abrupt break shown in the first diagram at *F*, where a boundary curve is met and a new phase appears, likewise shows up in the second diagram. This is of general applicability. In some instances the break may be less abrupt than in Figure 15, and exceptionally there may be only a gradual change of direction,

represented by a curve; in other instances the break may be more abrupt. In general, wherever a boundary curve is met, that is, wherever a new mineral joins the crystallizing assemblage, we expect a break or perceptible change of direction to appear on each of the lines of such a diagram as Figure 15.

In the Katmai effusive rocks the minerals or crystal phases are olivine, plagioclase, magnetite, hypersthene, augite, and quartz. If the differentiation was due to abstraction of crystals, the appearance of each of these minerals in succession (after the first) should lead to a break or change of direction. In the plutonic rocks the chief ferromagnesian minerals are hornblende and biotite, and this difference of mineral make-up should have caused differentiation to follow another course almost from the beginning. In spite of all this, differentiation of all rocks followed the same nearly linear course. Where aberrations occur they do not show a tendency to extend into distant fields, changing the linear directions thenceforward, but have the appearance of being peculiarities of the given rock—secondary effects imposed upon a magma differentiated primarily in a linear manner. The small variations fall first upon one side of a line and then upon the other.

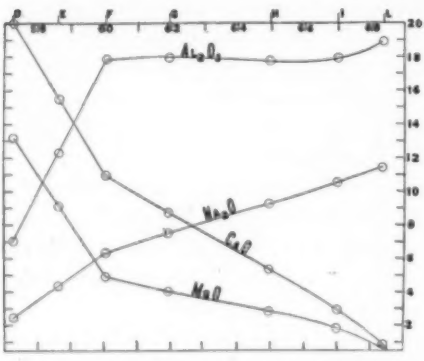

FIG. 15.—Two-co-ordinate variation diagram of a portion of the albite-anorthite-diopside system, illustrating effect upon composition of residual liquid, produced by crystallization. Basic oxides are plotted against silica.

The inference that breaks or changes of direction appear whenever a new mineral joins the crystallizing assemblage holds strictly only when crystals are removed immediately upon formation. If crystals settle slowly, or if a mineral such as magnetite, which forms small crystals, does not settle out in proper relative amount, the

composition of liquid plus suspended crystals is modified. It might be thought that from such causes the linear relation might fortuitously appear. This can hardly be so. The effect of such factors is to scatter the indicative points over a wide band, and though it might not be possible to decide where the mean line should be drawn or whether changes of direction are present, it would hardly be possible to have the points adhere closely to straight lines.

There is direct evidence in some of the Katmai rocks that failure of the magma to free itself promptly of crystals is not the explanation of the linear diagram. Specimen No. 104 shows plentiful phenocrysts of feldspar (oligoclase-albite) and quartz, and a few phenocrysts of pyroxene and magnetite, in a glass base. Now if it be supposed that in the more basic magmas of the series the withdrawal of feldspar, pyroxene, and magnetite had caused variation to follow a rectilinear course for a certain distance, then when quartz appeared in addition a change of direction should have followed, unless the quartz remained with the liquid while the others continued to settle as before. But the quartz is of almost the same specific gravity as the feldspar, and if quartz remains with the liquid, the feldspar should also, and the feldspar is part of a continuous series extending far back to basic magmas. The supposition that quartz was not removed, and thus no break was necessitated, therefore involves the supposition that feldspar ceased to be removed, and thus a break was required.

Moreover, even a supposition that quartz remained with the liquid while feldspar settled out is contradicted when we examine the next specimen of the analyzed series, No. 175. This should have retained all the quartz, as no break in the lines has appeared, but instead, we find that it is almost wholly glass, with only a few scattering crystals of quartz and feldspar. Every supposition that can be made to explain differentiation in this series by crystallization seems to be contradicted by several forms of evidence.

The conclusions may be summarized as follows:

a) Complete separation of crystals from liquid as soon as formed causes the successive compositions of the liquid to follow exactly a series of lines, all of which show breaks or perceptible changes of

direction at the points where each new mineral appears. The parts of the lines between the breaks may be either nearly straight or considerably curved.

This statement applies also to successive portions of the deposited solid, but the indicative points will not be the same as for the liquid.

b) If differentiation be effected by settling of crystals in somewhat promiscuous fashion, the broken line characteristic will apply to the liquid portion of the magma, but not to the mixture of liquid and crystals. The presence of suspended crystals will cause a scattering of points which may conceal the relations. The Palisade diagram (Fig. 12) is apparently largely of this type.

c) A close adherence of points to straight lines over a range which includes the successive appearance of a number of crystalline phases does not appear to be a possible result of the separation of crystals under any conditions. If a diagram shows this characteristic, it is thought that differentiation must be ascribed to some other process, and that the bulk composition of the fractions so produced was not essentially affected by crystallization.

FURTHER DISCUSSION OF THE KATMAI DIAGRAM

In the Katmai rocks variation is essentially rectilinear from one side of the diagram to the other. The aberrations show no tendency to extend into distant fields, and are so small as to seem consistent with the effect of subsidiary processes acting upon portions of magma differentiated by one primary principle.

Straight lines are mathematically simple, and if we regard the diagram from this standpoint, we see two possible methods by which, in the most general sense, straight-line variation might be brought about.

1. If two substances be mixed in various proportions, and if we plot any ingredient against any other, the compositions of all mixtures will lie on straight lines. Some such idea was involved in Bunsen's old theory, by which he derived all igneous rocks from two magmas—the normal trachytic and the normal pyroxenic—but present-day petrologists are generally agreed that there are too many objections for an acceptance of Bunsen's hypothesis as a universal principle. In a more restricted sense linear variation may be ex-

pected to hold approximately for hybrid rocks, formed either by the mingling of two magmas or by the assimilation of solid material by a magma. Even here a strict adherence to linear variation cannot be expected if extraneous processes lead to differential removal of material, and Harker has shown that in certain plutonic rocks of Skye differential removal led to notable departure from the linear relationship. It would seem, then, that unless the period of coexistence after mixture is short, it is not safe to assume that the linear character will be maintained.[1]

The coexistence, in close proximity, of two separate reservoirs of magma, one basic and the other acid, for a period of tens or hundreds of thousands of years, is so difficult to reconcile with other phenomena that the idea may probably be dismissed. The fact that at times an outbreak of one kind of magma is followed very shortly by that of a very different magma can probably be explained by less radical assumptions.

2. The second method by which a linear variation may be derived is practically the converse of the first. If we start with a magma whose composition we represent by a vertical series of points on a diagram similar to Figure 7, and if by any process whatever we abstract material whose composition is represented by a similar series of points to the left of the first, the composition of the magma will move to the right along lines which are the prolongation to the right of the lines connecting the corresponding points of each group. The rectilinear movement to the right may continue by the abstraction of more and more material of the same composition as at the start, or the rectilinear advance may be maintained by the abstraction of material whose composition itself changes along the same straight lines.

From an arithmetical standpoint, the abstracted material may be solid, liquid, or gaseous. The only restriction is that its composition be fixed or that it vary in the definite manner stated, but this restriction is important. Crystalline material will comply with the condition only as long as its bulk composition is fixed or varies con-

[1] In a number of analyses not yet published I have found that very considerable variations took place in the pumices ejected from Katmai in the 1912 eruption, and that this variation is essentially rectilinear. The variation in this case seems best explained by assimilation of old rocks.

tinuously, but will not comply when a discontinuity is introduced, such as that represented by the addition of a new mineral to the crystallizing assemblage, or by reactions which transform one mineral into another. This has already been brought out in connection with the albite-anorthite-diopside diagram.

Now, in complex mixtures, crystallization diagrams or models are always divided into distinct fields, separated by boundary curves, and it is this characteristic which requires breaks to appear on a two-co-ordinate diagram. If we should represent on a similar diagram changes in the composition of a complex liquid brought about by volatilization, such breaks would not ordinarily appear, for the simple reason that, although the composition of the volatilized material may change greatly, the change proceeds through insensible gradations. In other words, the discontinuous variations represented by crystalline phases are replaced by one continuously varying gaseous phase. To this degree, therefore, volatilization is more competent than crystallization to produce the desired result; it will at least give continuous lines rather than broken lines.

However, this does not by any means solve completely the problem of the straight-line diagram. The difficulty is that, although continuous variation is indicated as a result of volatilization, there is no apparent reason why the lines should be straight rather than curved. The straightness is a very remarkable characteristic and imposes further restrictions. Expressed mathematically, it means that the equation representing the process is of the first degree between two variables. If the Katmai diagram were the only one to show it, it might be regarded as fortuitous, but many other diagrams show a decided tendency to assume this form over a large part of their range.

Moreover, although volatilization, as an abstract conception, answers certain theoretical requirements in some cases better than other processes, we should require more definite evidence than is now available that it is of a potency to meet the very severe requirements demanded of it as a transporting agent before assigning to it such a large rôle in differentiation.

If we regard matters in as unbiased a manner as possible I think we shall have to admit that for most of the differentiated igneous bodies that have been studied there is not yet apparent any complete explanation as to the cause or causes of variation. Gaseous

transfer, crystallization differentiation, assimilation of foreign material, and mingling of magmas have apparently each played a prominent part in one or another described instance, but it is impossible to say what is the quantitative importance of any one of these in volcanism as a whole, or whether there may not be still other important processes.

It is much better to recognize this situation and be on the lookout for new evidence than to accept any one explanation as of universal applicability.

SUMMARY

Analyses have been made of a series of igneous rocks of the Katmai district, representing typical specimens of various compositions, modes of occurrence, and age. The results are tabulated and plotted on a variation diagram. A description of the field relations and the petrography of the rocks is given. Several additional analyses of rocks from adjacent areas have been made for comparison.

The plot of analyses of Katmai rocks shows an almost linear variation of constituents over a wide range. This characteristic is discussed with relation to processes of differentiation, and this involves a consideration of present-day theories of differentiation. A view which within recent years has attracted much attention is that of N. L. Bowen, which attributes differentiation of magmas almost wholly to processes by which crystals have been separated from residual liquid. This theory has been developed in a form so much more definite than other theories that it stands in a class by itself. It is possible to discuss its principles specifically and inquire into their validity.

The discussion naturally divides itself into two main parts. In the first, an inquiry is made as to whether, in phenomena described by competent geologists, any one process preponderates so greatly over others that the others may be considered negligible. It is shown that although there is evidence of the great importance of crystallization differentiation in some instances, many geologists have described occurrences which indicate that very great variations have been brought about by other processes also. The scale on which these processes have operated makes them appear of co-ordinate importance with crystallization differentiation.

The second subject for inquiry is as to whether the evidence

adduced for crystallization differentiation is as direct and unequivocal as has been supposed. With regard to field evidence, it is found that in some instances other interpretations seem equally justified. With regard to laboratory experiments, it is thought that conclusions derived from the investigation of simple systems have been extended to complex natural magmas with hardly sufficient allowance for the great differences of constitution. Specific instances are pointed out.

A fundamental feature of the theory, viz., the belief that the micropegmatitic mixture of quartz and feldspar in diabases and similar rocks represents the final residue from crystallization, and that this illustrates the method by which granitic magma has been formed, encounters conflicting evidence which raises a doubt as to the correctness of the interpretation. More evidence should be forthcoming in order to carry conviction that the direction of variation effected by crystallization corresponds to the course of differentiation by which the usual basalt-andesite-dacite-rhyolite rock series is developed.

The remarkable straight-line characteristic of the Katmai diagram is compared with the form of diagram that may be expected to result from the separation of successive crystalline phases. It is found that apparently any form of crystal separation is represented by a diagram of different character from the Katmai diagram. Crystallization differentiation, therefore, does not seem a competent process in explanation of the form of variation of the Katmai rocks.

Available evidence seems to show that, as causes of variation in the composition of igneous masses in general, the operation of a variety of processes is indicated, each of which has accomplished important results in certain described cases; but that the linear variation typified by the rocks of the Katmai area and found in slightly less definite expression in other areas imposes requirements of a kind which no process has yet been shown competent to fulfil. It is thought that more information is requisite before a complete solution of the problems of differentiation can be attained.

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